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# **Soil Freeze–Thaw Effects on Bank Erosion and Stability: Connecticut River Field Site, Norwich, Vermont**

Michael G. Ferrick, Lawrence W. Gatto,  
and Steven A. Grant

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**ABSTRACT:** Bank recession resulting from surficial erosion and mass failure is a consequence of hydraulic forces and geotechnical processes. One important set of geotechnical processes in regions where seasonal frost forms is soil freeze-thaw (FT) cycling and associated ground-ice growth and melt. In cold regions soil FT processes usually cause more bank recession annually than other processes. The magnitude of FT effects is variable, depending on soil type, water content, and freezing rate. The banks along the Connecticut River at Norwich, Vermont are unstable and receding in certain locations. A 40-m-long segment of unstable east-facing bank was selected for intensive monitoring along with nearby north- and south-facing bank locations. This technical note documents our field observations, measurements, and analysis encompassing three years of monitoring. Our data acquisition equipment, focusing on FT processes, was installed in November through December 2002, and data collection continued through July 2005. The primary purposes of the field program were to evaluate: 1) the depth and duration of soil FT, and the effect of orientation and soil moisture on these parameters, 2) the effects of FT on soil strength and erosional processes, 3) the timing and depth of any slope failures of the east-facing bank, and 4) the hypothesis of soil FT as a primary contributor to slope failure. Results indicate that bank orientation and soil moisture can have dramatic effects on the depth, extent, and duration of soil freezing. FT of the monitored banks generally affected the soil to a depth of 0.75 m below the surface. The shallow nature of the bank erosion at this site is consistent with FT weakening of near surface soils. Subsequent rainfall and runoff are then able to readily move these sediments down slope causing progressive bank recession. Finally, transport of fine eroded sediments and native soils from the base of the bank by waves and water level fluctuations maintain the slope in an unstable state to continue the bank erosion and recession.

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## PREFACE

This report was prepared by Michael G. Ferrick, Lawrence W. Gatto, and Dr. Steven A. Grant, Environmental Sciences Branch, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory.

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The Commander of the Engineer Research and Development Center is COL James R. Rowen. The Director is Dr. James R. Houston.

# **Soil Freeze–Thaw Effects on Bank Erosion and Stability: Connecticut River Field Site, Norwich, Vermont**

MICHAEL G. FERRICK, LAWRENCE W. GATTO, AND STEVEN A. GRANT

## **1 INTRODUCTION**

Bank recession resulting from erosion and mass failure is a consequence of hydraulic forces and soil mechanical processes. Simon et al. (1999) summarize the principal hydraulic and geotechnical processes and conditions affecting bank recession. Typical hydraulic processes include elevated river levels and velocities, wave attack at the base of shoreline banks, rill and overland runoff down the banks, and groundwater emergence at the bank face. Geotechnical processes and soil conditions interact temporally and spatially with these hydraulic processes to determine the amount of erosion and extent of failure at a specific location. One important set of geotechnical processes is soil freeze–thaw (FT) cycling and associated ground-ice growth and melt. Much previous research indicates that soil FT cycling causes 30–90% of bank failures (Thorne 1978, Sterrett 1980, Gardiner 1983, Reid 1985, Lawler 1993, Chase et al. 2001). And yet, Benoit and Voorhees (1990) and Kok and McCool (1990) report that FT cycling effects are among the least understood aspects of the soil-erosion process.

For areas where seasonal frost forms, previous studies show that processes related to bank soil FT usually cause more bank recession annually than other processes (Renard et al. 1997). During soil freezing, pore water can be drawn to the freezing front, forming pore ice, ice lenses, or ice layers. Ice-rich, frozen soils have high mechanical strength and low susceptibility to erosion and failure. However, the formation of pore ice crystals can also disaggregate a soil, which can disrupt the soil structure and decrease bulk density. Upon thaw, this soil is less cohesive, dense, and strong, making it more erodible and unstable (Gatto et al. 2001, Simon et al. 2000). The strength of a thawed soil often represents the annual low. In addition, the unit weight of a thawed soil is often higher than it was initially, owing to the accumulation of water during freezing. This added weight further increases the susceptibility of a thawed soil to mass failure and



water erosion in the spring (Gatto 2000). Consequently, spring floods often erode much more bank soil than floods of equal magnitude occurring later in the year after these soils have regained strength.

The variable magnitude of FT effects depends on soil type, water content, and freezing rate (Ferrick and Gatto 2005). The most frost-susceptible soils are composed of cohesive, silty sediments. Silts readily absorb water because the particles are small enough to provide relatively high capillary rise and large enough to furnish voids of adequate size to allow quick flow of water (Jumikis 1962). These characteristics lead to rapid saturation of the voids in silty soils during freezing. Coarser-grained soils do not retain a significant volume of water after wetting, and finer-grained soils do not absorb water rapidly enough. However, Janson (1963) reported that sand may become frost susceptible if it is well compacted, and Chamberlain\* found that needle ice will form in almost any soil.

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\* Personal communication with E. Chamberlain, USACRREL, 1978.

## 2 OBJECTIVES

Bank soil structure, cohesion, angle of internal friction, and bulk density, all of which vary seasonally because of frost effects, are used to derive soil erodibility coefficients in bank-erosion models. However, most models do not adjust these coefficients to account for this major seasonal variation, severely reducing model applicability in northern climes. Bank erosion and stability models must account for the effects of FT dynamics, including FT-induced changes to soil-mechanical conditions and relationships.

The original goal of this research was to provide the understanding of FT-induced changes to allow models such as that of Osman and Thorne (1988) to be modified for application in cold regions. Our research plan was to use field data in concert with data from controlled laboratory experiments to determine the relationships among bank-failures, soil-moisture redistribution, and thaw weakening caused by soil FT cycling. Analysis of such a suite of data could provide the quantitative understanding needed to modify existing models. However, because of inadequate funding, this comprehensive research plan could not be completed. This technical note documents field observations, measurements, and analysis of data obtained during 3 years of monitoring east-facing, north-facing, and south-facing banks along the Connecticut River at Norwich, Vermont. A focus of the work was to relate FT cycling effects to associated bank failure and recession.

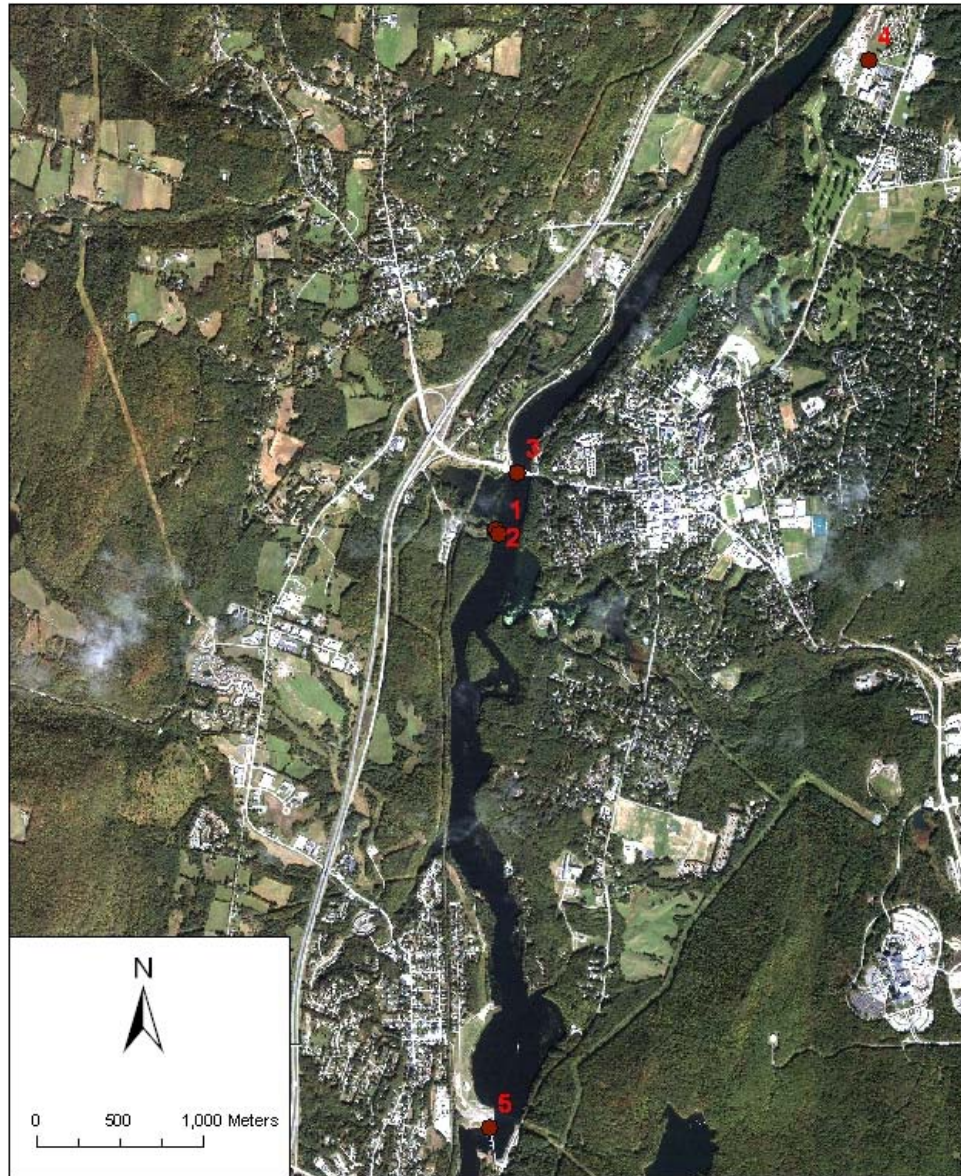
### 3 SITE DESCRIPTION

The banks along the Connecticut River at the monitored sites are approximately 4-m high, with slopes of about 52°, all in the town of Norwich, Windsor County, Vermont. Figure 1 shows the reach of the river, which includes the study sites, from Wilder Dam in the south upstream to CRREL. The south-facing bank site is located immediately south of the western abutment of the Ledyard Bridge between Norwich and Hanover, New Hampshire. The approximate coordinates of this site (reference WGS84/NAD83 datum) are UTM 18 717436E 4842447N. The soil at this site was mapped as an udorthent or an udipsamment, and the vegetation is grass and brush. The north-facing and east-facing bank sites are located across one large and one small inlet south of the south-facing site, directly east of the Montshire Museum. The approximate coordinates of these sites are UTM 18 717395E 4842127N. Mechanical analysis by Villars\* indicated that the soil at these sites should be classified as either a Hartland silt (a coarse-silty, mixed, active, mesic Dystric Eutrudept) or Unadilla silt (a coarse-silty, mixed, active, mesic Typic Dystrudept). Vegetation is mixed forest, including oak, beech, sugar and red maple, hemlock, and white pine.

Survey lines denoted “upstream,” “instrument,” and “downstream” profile the east-facing bank and delineate the study reach. The surveyed profile lines were photographed to visually characterize the site. Figure 2, taken in July 2005, shows the heavily vegetated “upstream” bank profile line. About 15 m downstream of this line is the “instrument” bank profile line, depicted in Figures 3, 4, and 5. Figure 3 shows variable snow depth on the bank and ice cover on the river in March 2003. Figure 4 shows this location in July 2005 with the bank-face instrument clusters highlighted by arrows. Figure 5 presents close-up views of a sediment source and resulting cavity just below the forest root mat (Fig. 5a), and deposition of this sediment on the bank face at the lower instrument cluster near the base (Fig. 5b). A close-up of the natural rock armoring developed at the base of the bank is shown in Figure 6. Finally, Figure 7 shows the revegetating “downstream” bank profile line in July 2005, about 25 m downstream of the instrument line.

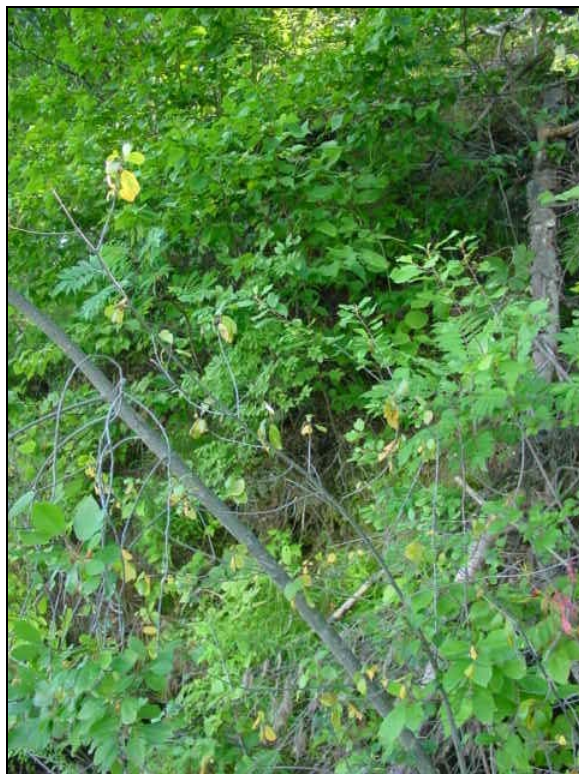
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\* Personal communication with T. Villars, NRCS-USDA, 2004.



**Figure 1.** Aerial photograph showing location of the Connecticut River reach that contains the study sites. The river is the border between New Hampshire (east bank) and Vermont (west bank). The urban area in New Hampshire is the town of Hanover, and the interstate highway in Vermont is I-91. The numbered bank recession study locations are: 1) north-facing bank site; 2) east-facing bank site; 3) south-facing bank site; 4) meteorological station at CRREL; and 5) Wilder Dam.





**Figure 2. Densely vegetated “upstream” bank profile line from July 2005.**



**Figure 3. “Instrument” bank profile line from winter 2003.**



a. From slightly upstream.



b. From slightly downstream.

Figure 4. “Instrument” bank profile line from summer 2005, with bank-face instrument clusters indicated by arrows.





**a. Top of bank sediment loss from just below the vegetated forest floor.**



**b. Sediment deposition, from the source above, on the bank surface near the lower instrument cluster.**

**Figure 5. Close-ups of “instrument” bank profile line from July 2005.**



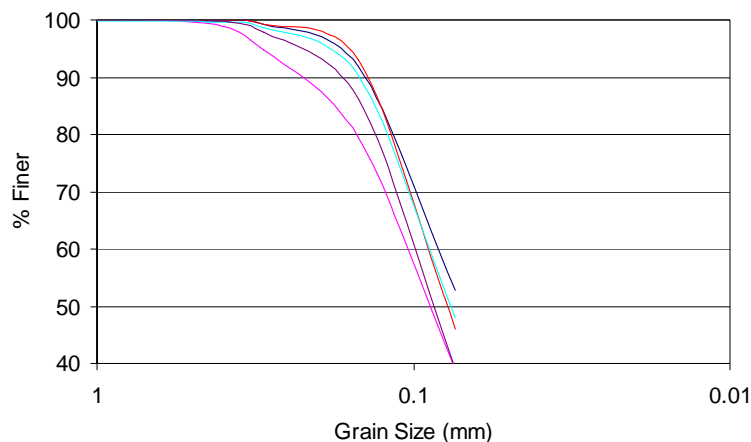
**Figure 6. Close-up of natural rock armor that has developed at the base of the receding bank.**



**Figure 7. Revegetating “downstream” bank profile line from summer 2005.**



Five soil samples were obtained on 18 June 2003 from the east-facing bank between the upstream and downstream profile lines and between 0.5 and 3.7 m above the water line. On average, 55% of the bank soil is very fine to coarse sand, 30% is very fine to coarse silt, and 15% is clay-sized. Figure 8, giving the particle-size distributions from sieve analysis, clearly indicates measurable variability among the samples. In addition, Table 1 provides moist and dry unit weights, void ratios, porosities, gravimetric and volumetric moisture contents, and saturation of these soils at the time of sampling. Soil moisture varied significantly among the samples, but porosity was uniformly high. During instrument installation, we noted that the soils of the nearby north-facing bank were similar to those of the east-facing bank.



**Figure 8. Soil particle size distributions from the east-facing bank between “upstream” and “downstream” profile lines.**

**Table 1. East-facing bank soil characteristics, Norwich, Vermont.**

| <b>Sample</b>                  | <b>Wet soil wt.<br/>(g)</b>          | <b>Dry soil wt.<br/>(g)</b>    | <b>Soil<br/>moisture (g)</b>                              | <b>Moist unit<br/>wt. (kg/L)</b>                              | <b>Dry unit wt.<br/>(kg/L)</b>           |
|--------------------------------|--------------------------------------|--------------------------------|---|---|--|
| 1                              | 414.8                                | 365.7                          | 49.1  | 1.408   | 1.242                                    |
| 2                              | 351.3                                | 322.4                          | 28.9  | 1.193   | 1.095                                    |
| 3                              | 430.5                                | 374.9                          | 55.6  | 1.462   | 1.273                                    |
| 4                              | 361.3                                | 330.9                          | 30.4  | 1.227   | 1.124                                    |
| 5                              | 337.8                                | 301.5                          | 36.4  | 1.147   | 1.024                                    |
| <b>Average</b>                 | <b>379.1</b>                         | <b>339.1</b>                   | <b>40.1</b>   | <b>1.287</b>  | <b>1.151</b>                             |
| <b>St. Dev.</b>                | <b>36.6</b>                          | <b>27.4</b>                    | <b>10.5</b>   | <b>0.124</b>  | <b>0.093</b>                             |
| <b>Coeff. of<br/>variation</b> | <b>0.097</b>                         | <b>0.081</b>                   | <b>0.262</b>  | <b>0.097</b>  | <b>0.081</b>                             |
| <b>Sample</b>                  | <b>Void Ratio<br/><math>e</math></b> | <b>Porosity <math>n</math></b> | <b>Gravimetric<br/>Mois. Cont.<br/><math>w</math> (%)</b> | <b>Volumetric<br/>Mois. Cont.<br/><math>\theta</math> (%)</b> | <b>Saturation<br/><math>S</math> (%)</b> |
| 1                              | 1.17                                 | 0.54                           | 0.134   | 16.7  | 0.309                                    |
| 2                              | 1.47                                 | 0.59                           | 0.090   | 9.9   | 0.165                                    |
| 3                              | 1.12                                 | 0.53                           | 0.148   | 19.0  | 0.357                                    |
| 4                              | 1.40                                 | 0.58                           | 0.092   | 10.4  | 0.177                                    |
| 5                              | 1.64                                 | 0.62                           | 0.121   | 12.4  | 0.199                                    |
| <b>Average</b>                 | <b>1.36</b>                          | <b>0.57</b>                    | <b>0.117</b>  | <b>13.7</b>   | <b>0.242</b>                             |
| <b>St. Dev.</b>                | <b>0.19</b>                          | <b>0.03</b>                    | <b>0.023</b>  | <b>3.6</b>  | <b>0.077</b>                             |
| <b>Coeff. of<br/>variation</b> | <b>0.14</b>                          | <b>0.06</b>                    | <b>0.197</b>  | <b>0.262</b>  | <b>0.319</b>                             |

## 4 INSTRUMENTATION

Soil temperature profiles allow estimation of the depth of soil frost and the number and duration of soil FT cycles. Important questions to be resolved by the data include the influence of bank orientation and soil moisture on the temperature regime. Water temperatures identify the ice-covered period of the river, which is readily observed. This period can be compared with those of the frozen ground at each profile location to assess and understand similarities and differences. Air temperatures provide the primary forcing to the soil and water temperatures. The temperatures obtained at the Norwich site could be compared and further interpreted with a much longer data record available for the open and flat meteorological site at CRREL located 3.6 km to the north and east (Fig. 1). CRREL met data includes snow depth, air temperature, and soil temperature at 10 cm. Such a comparison would quantify the influence of the forest cover on the air and shallow soil thermal regimes, and place the 3-year study in a broader climatic context.

To simplify the instrumentation and minimize cost, all temperatures were measured and recorded at 1-hour intervals with Onset Underwater StowAway TidBit data loggers.\* Our experience with these units indicates that they meet or exceed their published range of  $-20$  to  $50^{\circ}\text{C}$  and accuracy of  $\pm 0.4^{\circ}\text{C}$  at  $20^{\circ}\text{C}$ . In November 2002 we installed the following Onset temperature loggers:

- One was suspended from a tree branch about 1.5 m above the upland ground surface near the crest of the north-facing bank.
- Six were placed near the instrument line in the east-facing bank, one each at 10-, 25-, and 50-cm depths in the upper part of the bank about 3 m above the water, and one at each of these same depths in the lower bank at about 1 m above the water.
- Four were placed in the north-facing bank at 10-, 25-, 50-, and 75-cm depths about 1.5 m above the water.
- Three were placed in the south-facing bank at 10-, 25-, 50-cm depths about 3 m above the water.
- One was placed 50-cm deep in the upland surface along the instrument line about 1.7 m landward of the crest of the east-facing bank.
- One was placed on the river bottom in 47 cm of water about 5 m offshore of the east-facing bank.

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\* Onset, P.O. Box 3450, Pocasset, MA; [www.onsetcomp.com](http://www.onsetcomp.com)

On 19 December 2002, we completed the installation with three Onsets placed in the upland surface along the instrument line near the 50-cm-deep Onset at 10-, 25-, and 75-cm depths.

Volumetric soil-water content at 10-, 20-, 30-, 40-, 60-, and 100-cm depths was measured with a PR1/6 Profile Probe.\* On 8 November 2002, we installed seven PR1/6 probe access tubes as follows:

- Three in the east-facing bank on the instrument line, one near the top group of Onsets, one near the bottom group, and one about 0.5m above the water.
- Two in the upland surface on the instrument line 1.1 m (east) and 2.3 m (west) landward of the crest of the east-facing bank.
- Two in the north-facing bank, one in the upper bank and one in the mid-bank about 2 m below, with both tubes located above the group of Onsets.

Volumetric soil-water content of the upper 6 cm of soil was also measured with a ThetaProbe Type ML2x soil moisture sensor.† These surface-soil-water contents were measured together with soil strengths at the same time and at adjacent locations. Vane-shear strengths were measured with a Soiltest Model CL-612 Hand Vane Tester,‡ following the ASTM (2005) D2573 standard test method. Soil-penetration resistances were measured with a Soiltest Model CN-419A and CN-433A Proctor Penetrometer, following the ASTM (2005) D1558 standard test method.

Bank profiles along the profile lines were measured at intervals through the study period with a surveyor's level and rod. Vertical elevations were measured directly, and horizontal distances were obtained by reading stadia from the rod. Water surface elevations were initially measured offshore of the east-facing bank at an hourly interval with a Global Water WL-14 water logger.§ We installed the water logger on the river bottom on 22 November 2002 in 89 cm of water. These on-site data were compared with hourly headwater elevation data routinely collected at the Wilder Dam, 3.6 km downstream and due south (Fig. 1). These data sets were equivalent, so on-site collection was stopped and the Wilder Dam data were used to represent the time series of reservoir water levels.

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\* Delta-T Devices, Ltd., 128 Low Road, Burwell, Cambridge, CB5 0EJ, United Kingdom; [www.delta-t.co.uk](http://www.delta-t.co.uk)

† Delta-T Devices, Ltd.

‡ ELE International, P.O. 86 Albrecht Drive, Lake Bluff, IL 60044-8004; [www.ele.com](http://www.ele.com)

§ Global Water, Gold River, CA 95670; [www.globalw.com](http://www.globalw.com)

## 5 RESULTS

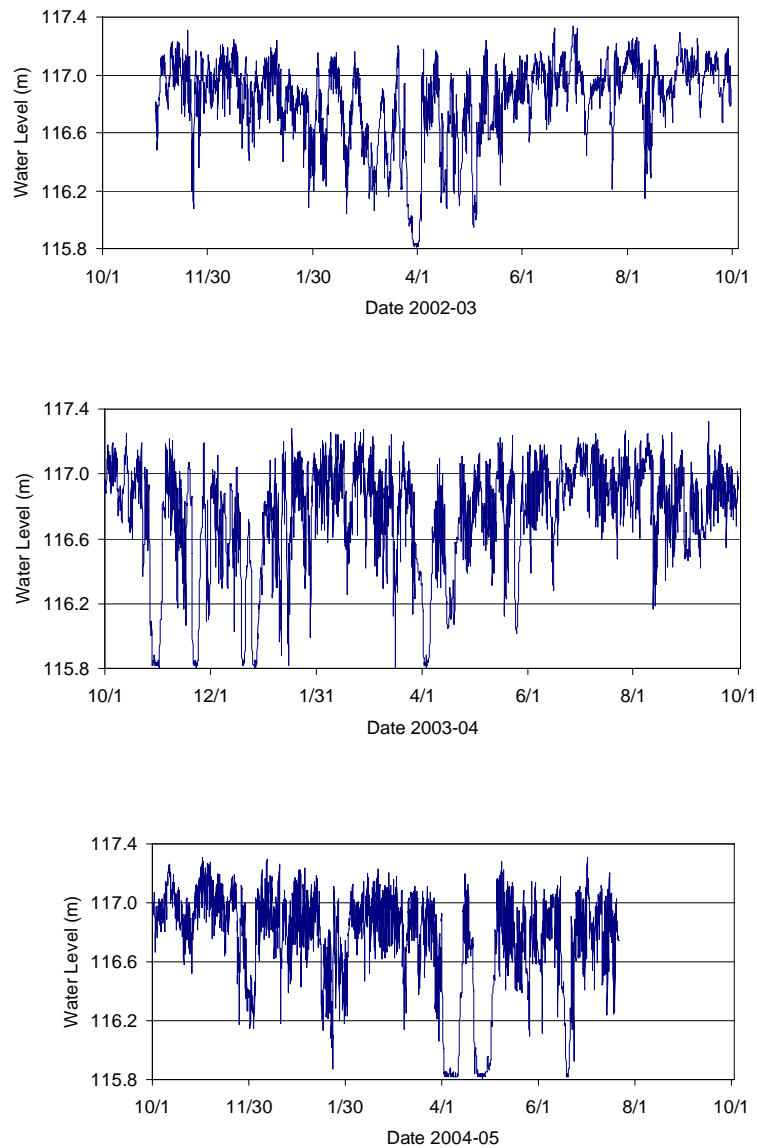
Data collection included both continuous measurements recorded on data loggers as well as manual measurements obtained during site visits. We begin this analysis by first considering the continuous data records. These data provide a context for the manual measurements that are considered subsequently.

### Connecticut River (Wilder Reservoir) Water Levels and Temperatures

Wilder Reservoir water levels are given by water year for the 3 years of the study in Figure 9. Water level fluctuations over a 1.5-m range represent normal operating conditions. Spring, fall, and winter drawdowns to the bottom of the operating range can be noted in Figure 9, and usually occur in anticipation of greatly increased runoff from the basin. At minimum pool there is a large beach adjacent to the monitored section of bank, while at pool levels of 117 m and above, the water makes direct contact with the bank. To better comprehend the water level data, Table 2 provides statistics through the study period in 6-month intervals for fall-winter and spring-summer. These intervals were selected so that each includes historical high flow (fall, spring) and low flow (winter, summer) periods. The mean, standard deviation, and range are all quite consistent through time for these intervals. The mean water level is about 0.25 m below the base of the bank, but higher water levels that directly contact the bank occur regularly throughout the year.

**Table 2. Wilder reservoir water level data summary.**

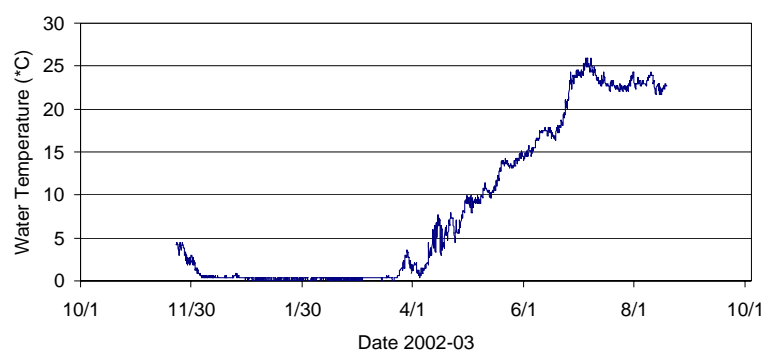
|             | 11/02–3/03 | 4/03–9/03 | 10/03–3/04 | 4/04–9/04 | 10/04–3/05 | 4/05–7/05 |
|-------------|------------|-----------|------------|-----------|------------|-----------|
| Mean (m)    | 116.78     | 116.86    | 116.70     | 116.80    | 116.87     | 116.56    |
| St Dev (m)  | 0.30       | 0.27      | 0.37       | 0.29      | 0.24       | 0.42      |
| Max. (m)    | 117.31     | 117.34    | 117.28     | 117.32    | 117.31     | 117.31    |
| Min. (m)    | 115.81     | 115.80    | 115.80     | 115.81    | 115.88     | 115.80    |
| Mean (ft)   | 383.14     | 383.41    | 382.88     | 383.19    | 383.42     | 382.41    |
| St Dev (ft) | 0.97       | 0.90      | 1.20       | 0.94      | 0.78       | 1.39      |
| Max. (ft)   | 384.86     | 384.96    | 384.78     | 384.91    | 384.88     | 384.86    |
| Min. (ft)   | 379.96     | 379.94    | 379.92     | 379.94    | 380.19     | 379.91    |



**Figure 9. Wilder Reservoir water level (m) throughout the study period.**

The period of ice cover on the reservoir can be discerned from water temperature measurements at the site, given in Figure 10 for the fall of 2002 through the summer of 2003. This water temperature record is abbreviated because the offshore logger was buried by sediment deposition and could not be retrieved for downloading the following summer. However, the ice-cover period and water temperature range recorded in 2002–03 are very typical of other years. The ice

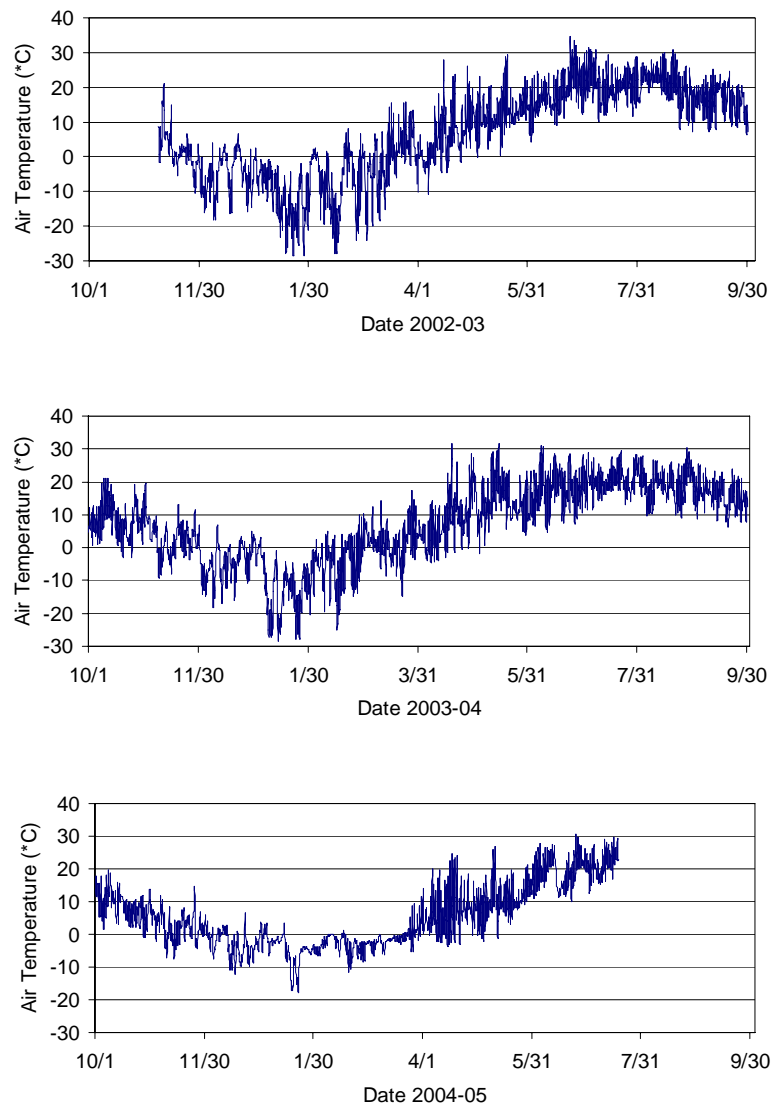
cover formed in early December, and persisted late into March. Ice formation began with the growth of shore-fast ice in protected areas. These ice shelves gradually expanded into the river, narrowing the width of open water until ice floes moving downstream bridge the channel. The ice cover formed in this low stream gradient environment is smooth, with an average late-winter thickness of about 50 cm. Ice breakup in this reach is largely thermal, with most of the ice melting in place. Water velocity near the monitored bank is generally low throughout the year as a result of the large 100-m wide and 6.5- to 8-m deep channel cross-section, reservoir drawdown at high flow, and sheltering by upstream shoals. As a result of all these factors, the impact of the river on bank recession at the site is limited to small waves and fluctuating water levels.



**Figure 10. Wilder Reservoir water temperature (°C).**

### **Air and Soil Temperatures**

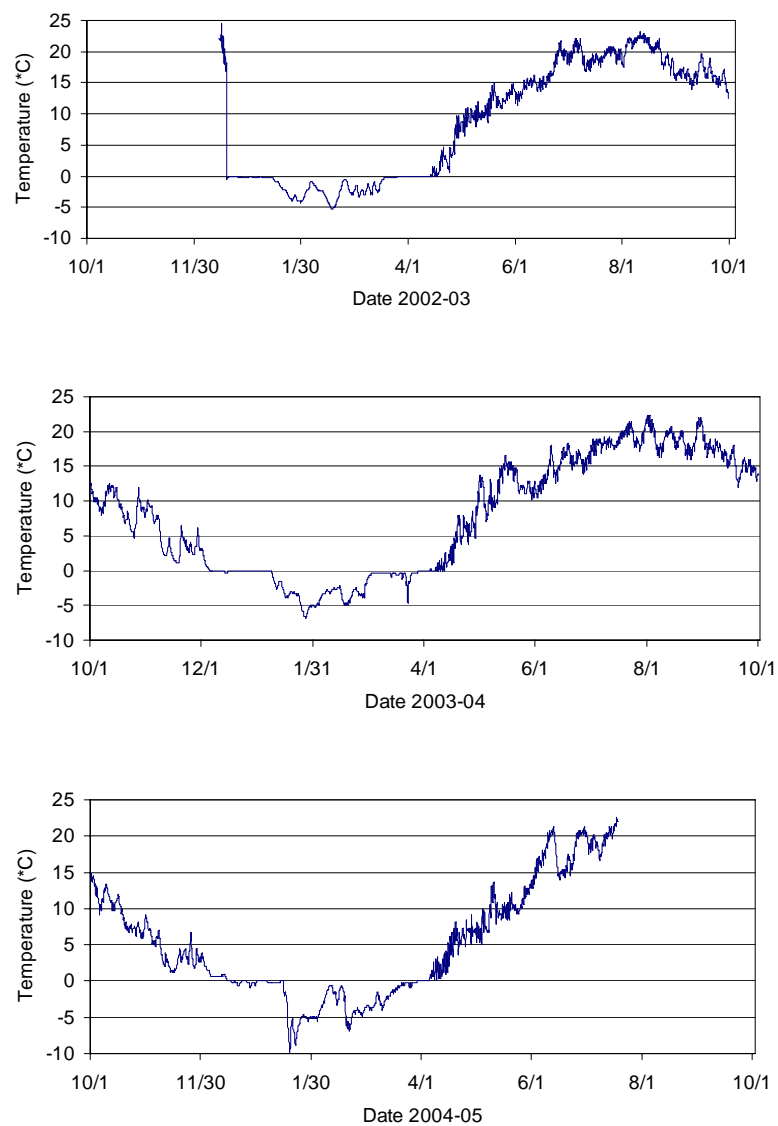
Air and soil temperatures were measured during the period from 8 November 2002 to 19 July 2005. Air temperatures measured at the top of the east-facing and north-facing banks, under the forest cover, are given in Figure 11 for the period of the study. These air temperatures and all subsequent soil temperatures are displayed by water year. The low-frequency seasonal and high frequency diurnal changes in air temperature can both be readily discerned. The period of sub-freezing air temperatures extends from the beginning of December until mid- to late March, well aligned with the ice cover period on the reservoir. Minimum temperatures in January approached  $-30^{\circ}\text{C}$  in 2 of the 3 years of data collection. Diurnal temperature changes often exceed  $20^{\circ}\text{C}$ , typically in winter and spring. Maximum air temperatures occur in June through August and frequently top  $30^{\circ}\text{C}$ .



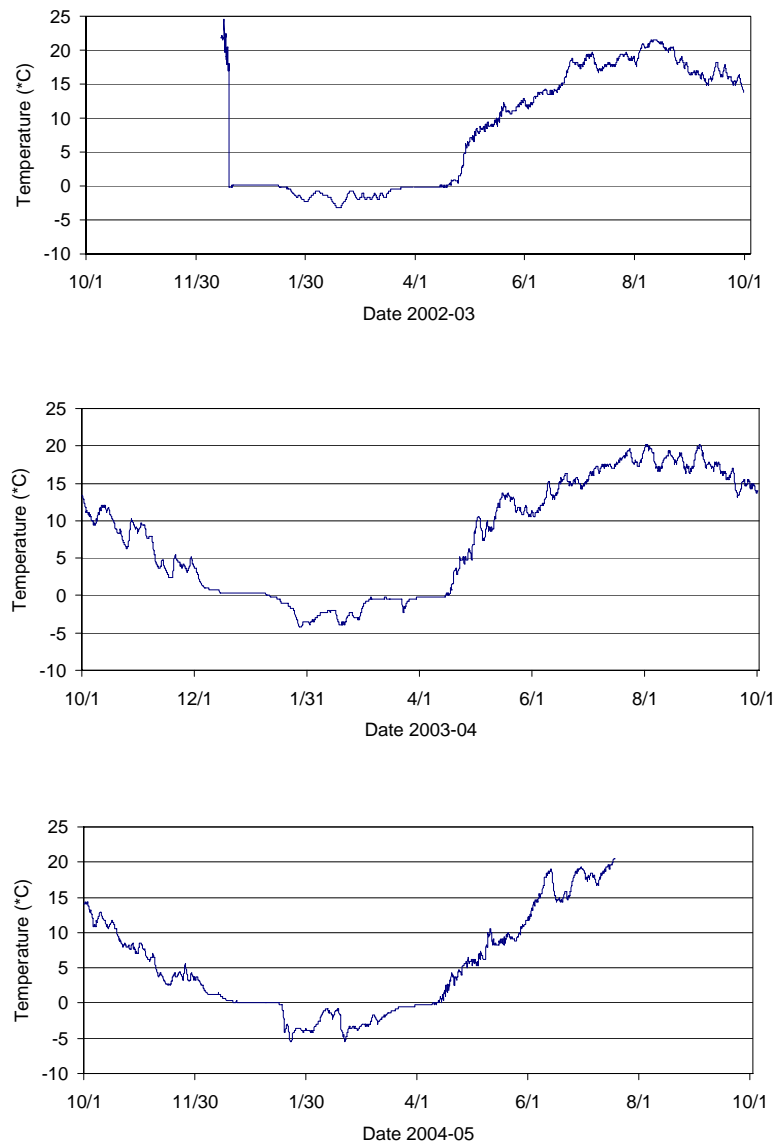
**Figure 11. Air temperature (°C) at 1.5 m above the ground on the upland surface and under the forest canopy at the east-facing and north-facing bank sites in Norwich, Vermont.**

Winter soil temperature comparisons indicate the importance of local conditions; specifically the presence or absence and depth of snow cover, exposure to solar radiation, and soil moisture. Soil temperatures at 10-, 25-, 50-, and 75-cm depths on the upland surface at the instrument bank profile line are given for each of the study years in Figures 12, 13, 14, and 15, respectively.

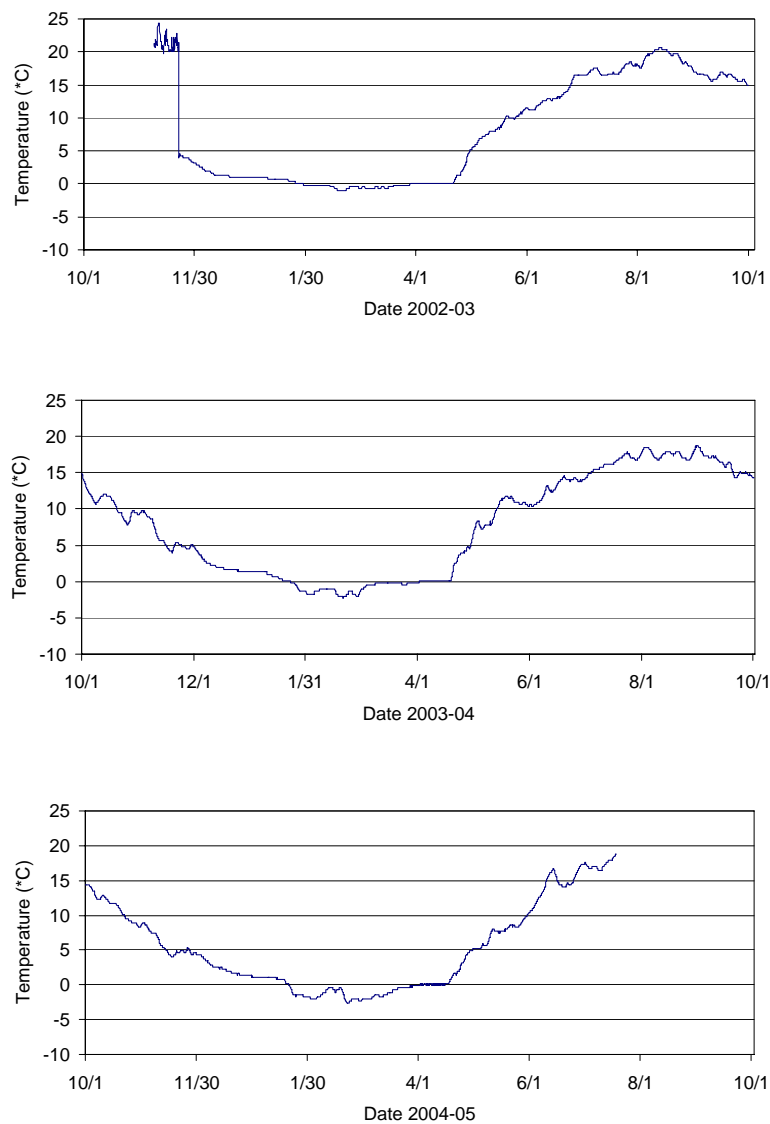




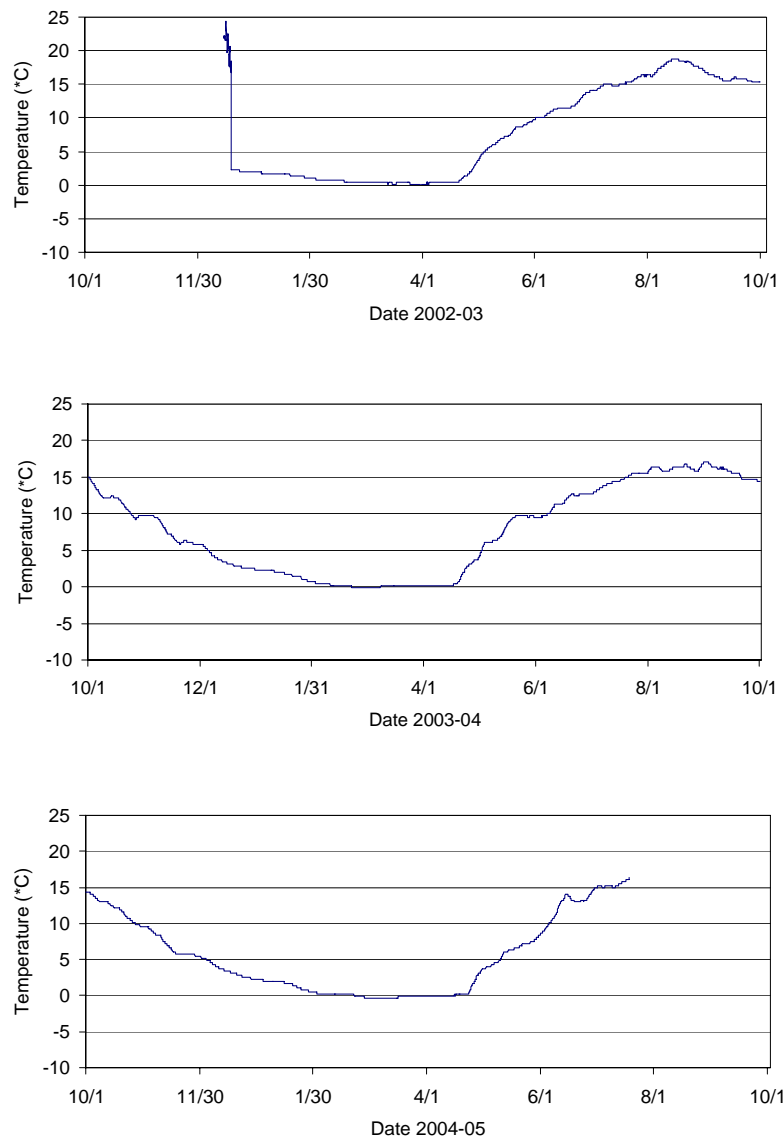
**Figure 12. Soil temperature (°C) at 10-cm depth on the up-land surface of the “instrument” bank profile line.**



**Figure 13. Soil temperature (°C) at 25-cm depth on the up-land surface of the “instrument” bank profile line.**



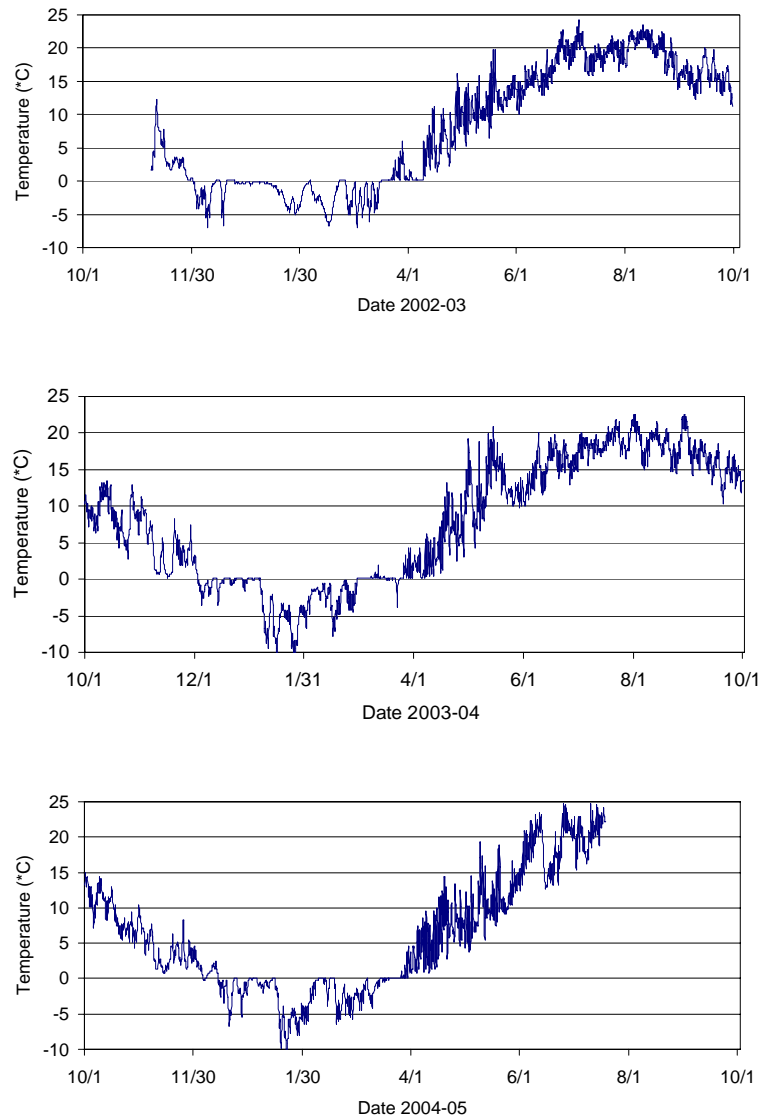
**Figure 14. Soil temperature (°C) at 50-cm depth on the up-land surface of the “instrument” bank profile line.**



**Figure 15. Soil temperature (°C) at 75-cm depth on the upland surface of the “instrument” bank profile line.**

Each data record required a period of time following installation before recording the actual soil temperature began. Diurnal and short-term temperature fluctuations are evident at the 10-cm depth (Fig. 12). Diurnal temperature fluctuations are greatly attenuated at 25 cm (Fig. 13), and short-term temperature fluctuations are barely visible at 75 cm (Fig 15). Another change in character that occurs over this depth range is a decreasing temperature range with increasing depth. The duration of soil freezing decreases and the minimum soil temperature

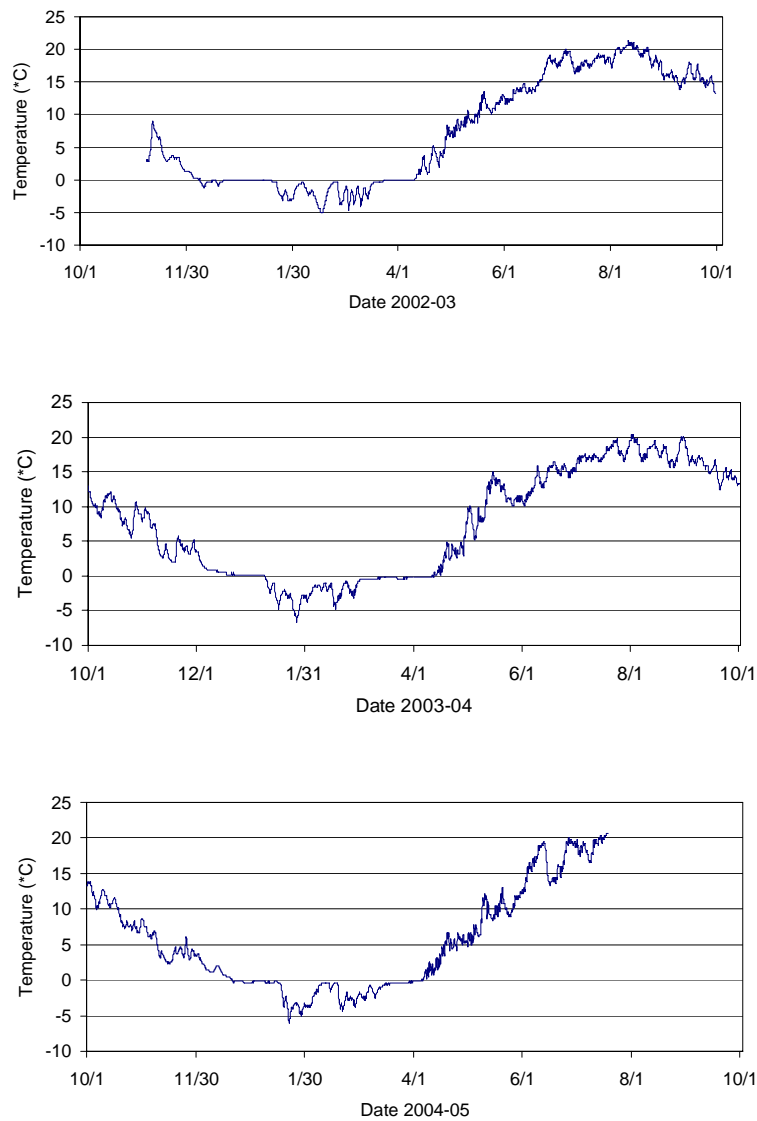
increases as depth increases. The depth of frozen soil extends below 50 cm at this upland location, with a freezing limit in each of the study years that is very close to 75 cm.



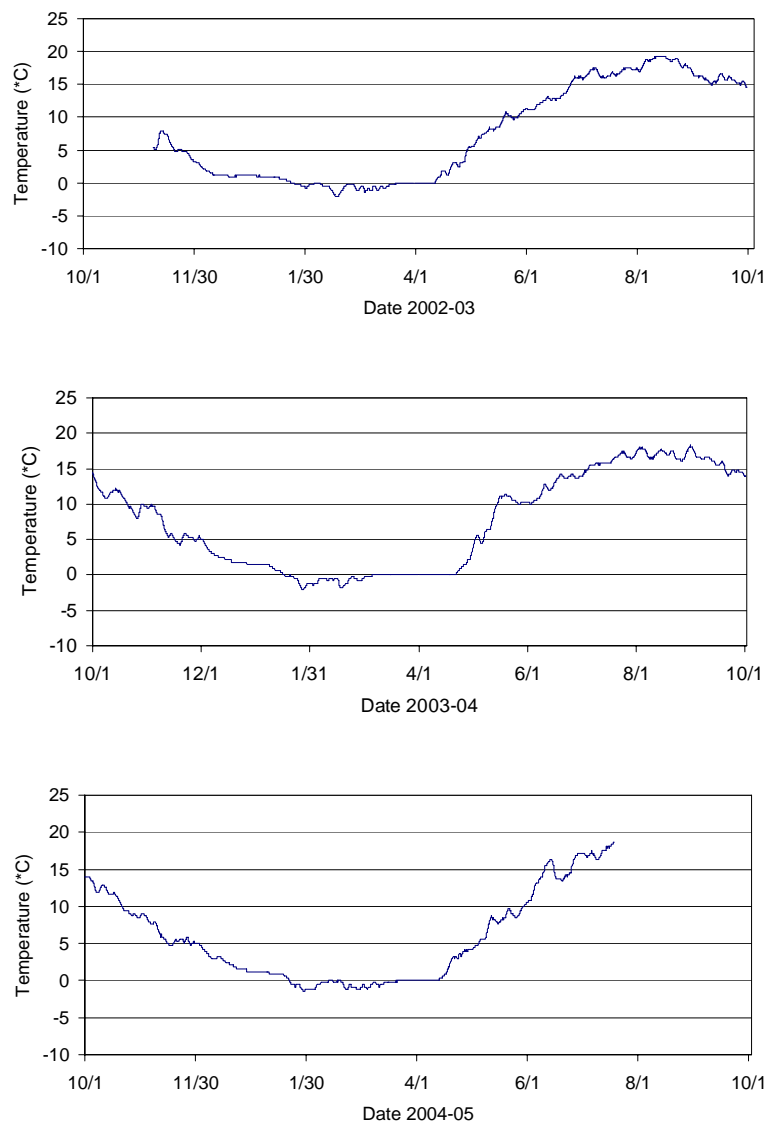
**Figure 16. Soil temperature (°C) at 10-cm depth in the upper east-facing cluster of the “instrument” bank profile line.**

The extent of soil freezing was very different at the upper and lower bank face sites on the instrument bank profile line, separated by less than 3 m. Soil

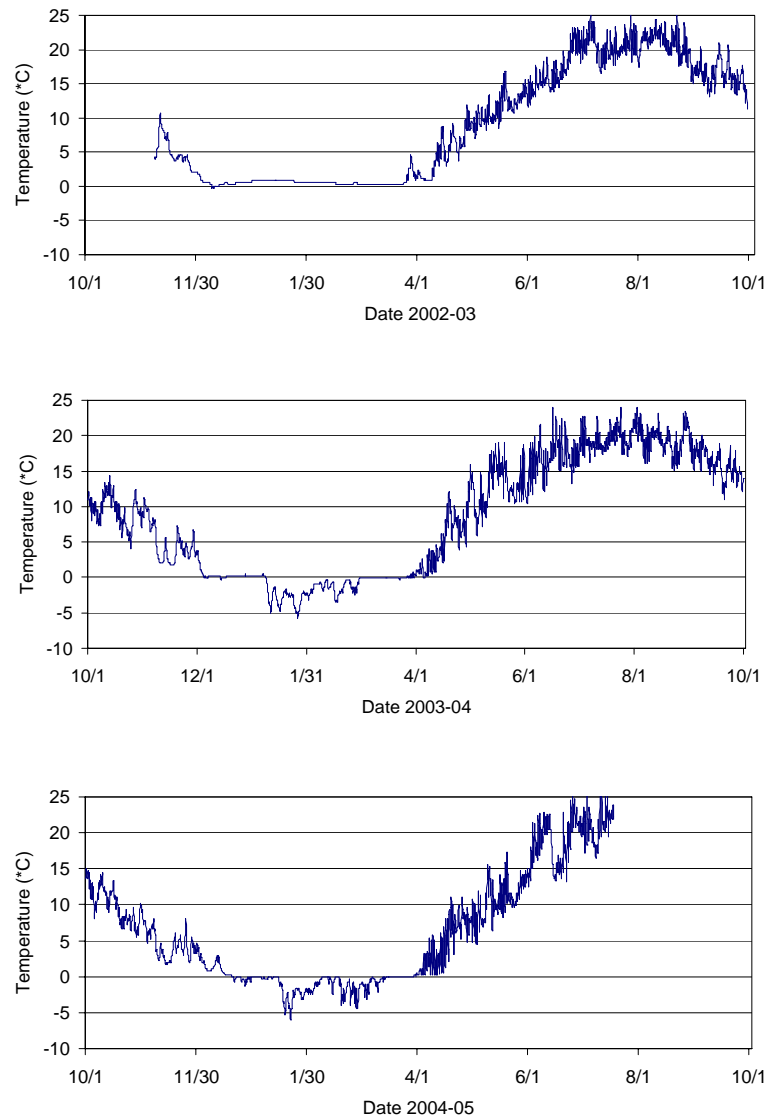
temperatures for the upper east-facing cluster at 10-, 25-, and 50-cm depths are given in Figures 16, 17, and 18, respectively, and corresponding soil temperatures for the lower east-facing cluster at the same depths are given in Figures 19, 20, and 21.



**Figure 17. Soil temperature (°C) at 25-cm depth in the upper east-facing cluster of the “instrument” bank profile line.**

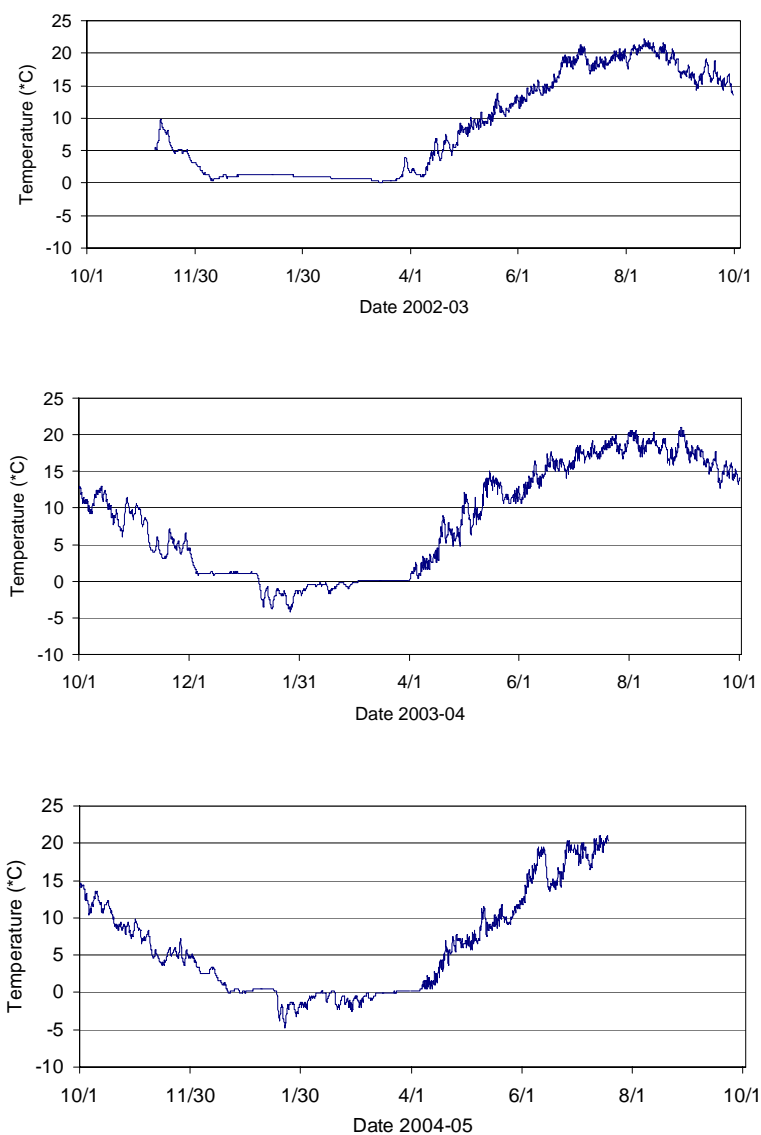


**Figure 18. Soil temperature (°C) at 50-cm depth in the upper east-facing cluster of the “instrument” bank profile line.**

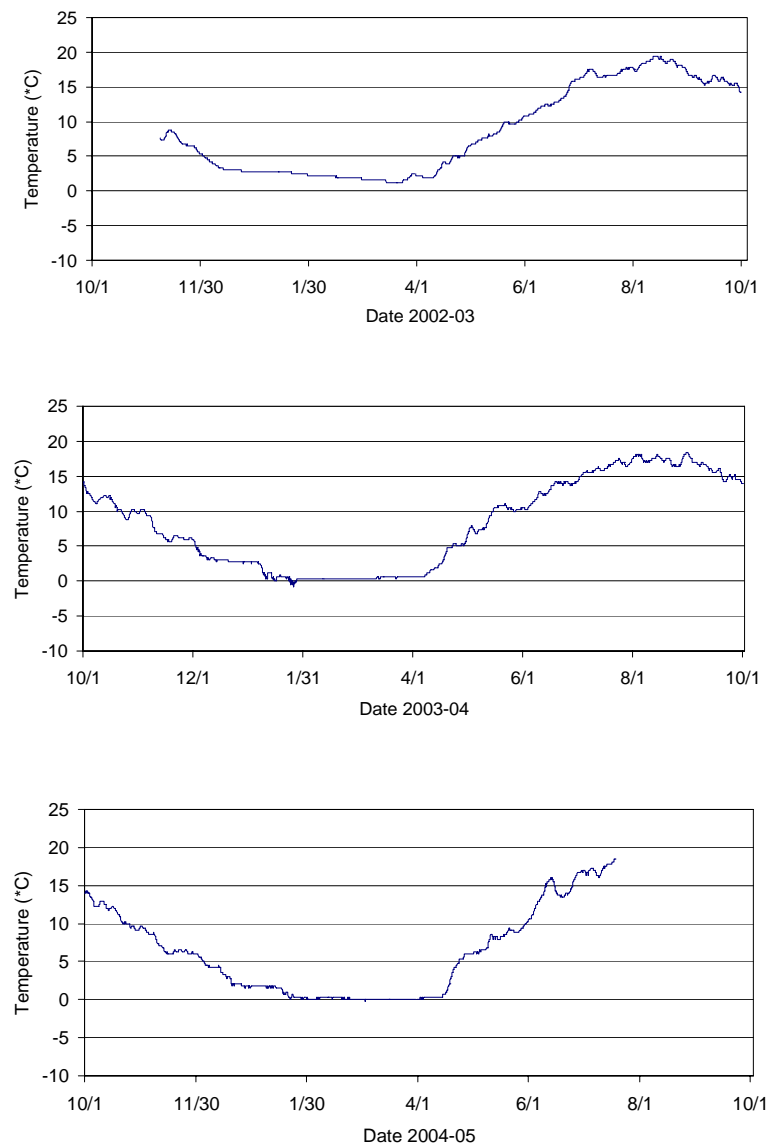


**Figure 19. Soil temperature (°C) at 10-cm depth in the lower east-facing cluster of the “instrument” bank profile line.**





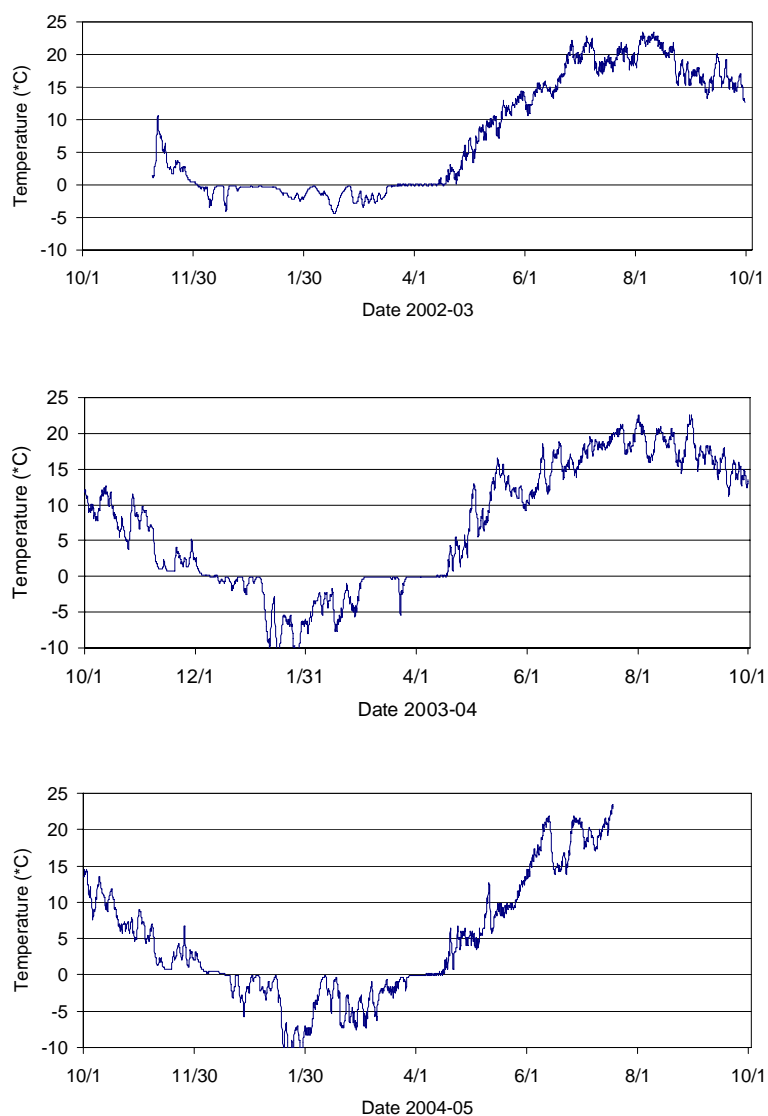
**Figure 20. Soil temperature (°C) at 25-cm depth in the lower east-facing cluster of the “instrument” bank profile line.**



**Figure 21. Soil temperature (°C) at 50-cm depth in the lower east-facing cluster of the “instrument” bank profile line.**

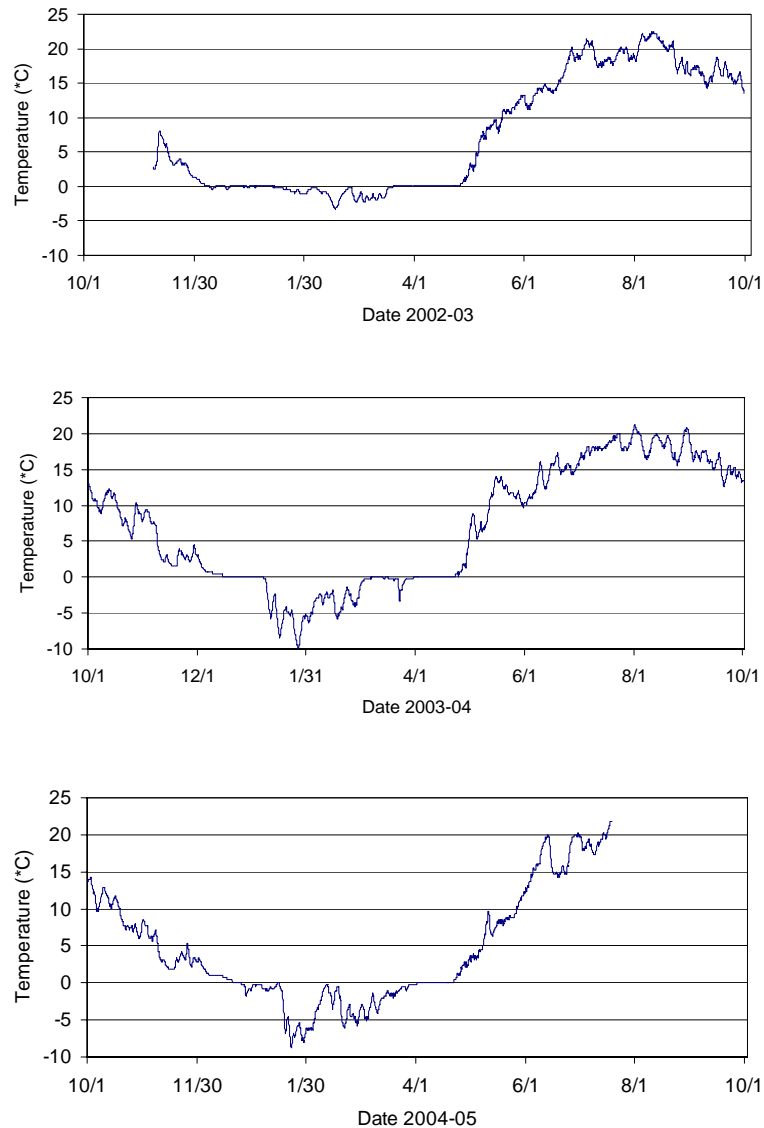
The upper bank face had freezing temperatures below 50 cm in each of the three winters. In 2002–03, the lower bank face site had minimal freezing at the 10-cm depth and no freezing with temperatures above 1.3°C throughout the winter at 50 cm. At the 10-cm depth in the other years, the upper site had greater diurnal temperature fluctuations and lower minimum temperatures than the same depth at the lower site. Freezing temperatures in 2003–04 and 2004–05 were

comparable between the upper and lower sites at 25 cm, but were again moderated at 50 cm for the lower site. The duration of upper bank soil freezing was always much greater than that of the lower site. Higher soil moisture and greater latent heat release during freezing contribute significant thermal inertia that moderates lower bank soil temperature change. Greater snow depths low on the bank (Fig. 3) may also act to reduce heat exchange and related changes in soil temperature.

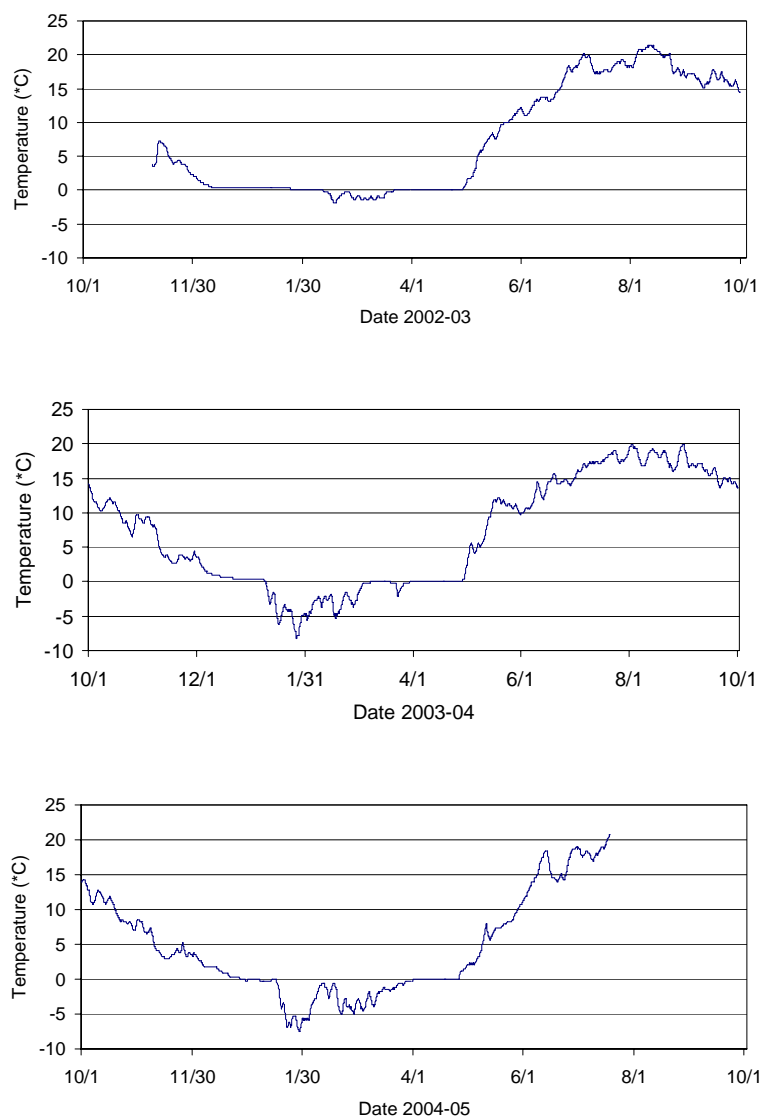


**Figure 22. Soil temperature (°C) at 10-cm depth in the north-facing bank.**

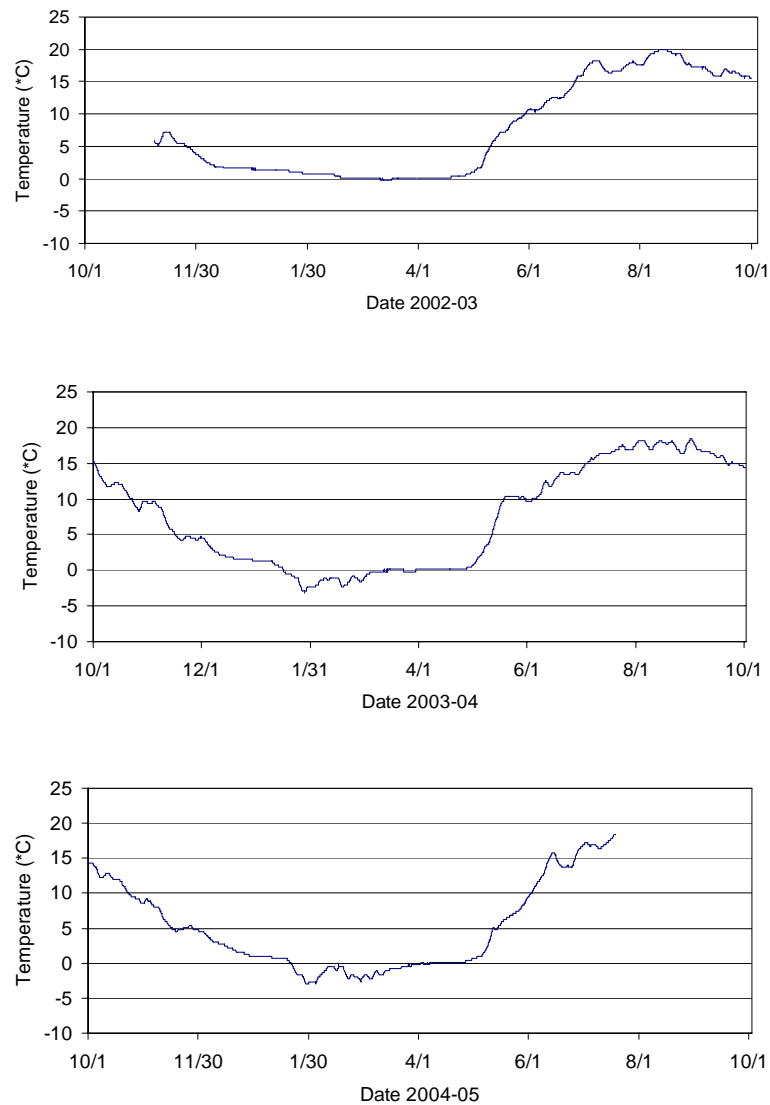
The orientation of the monitored bank was very important to the soil temperature regime. Soil temperatures of the north-facing bank are given in Figures 22, 23, 24, and 25 for the 10-, 25-, 50-, and 75-cm depths.



**Figure 23. Soil temperature (°C) at 25-cm depth in the north-facing bank.**



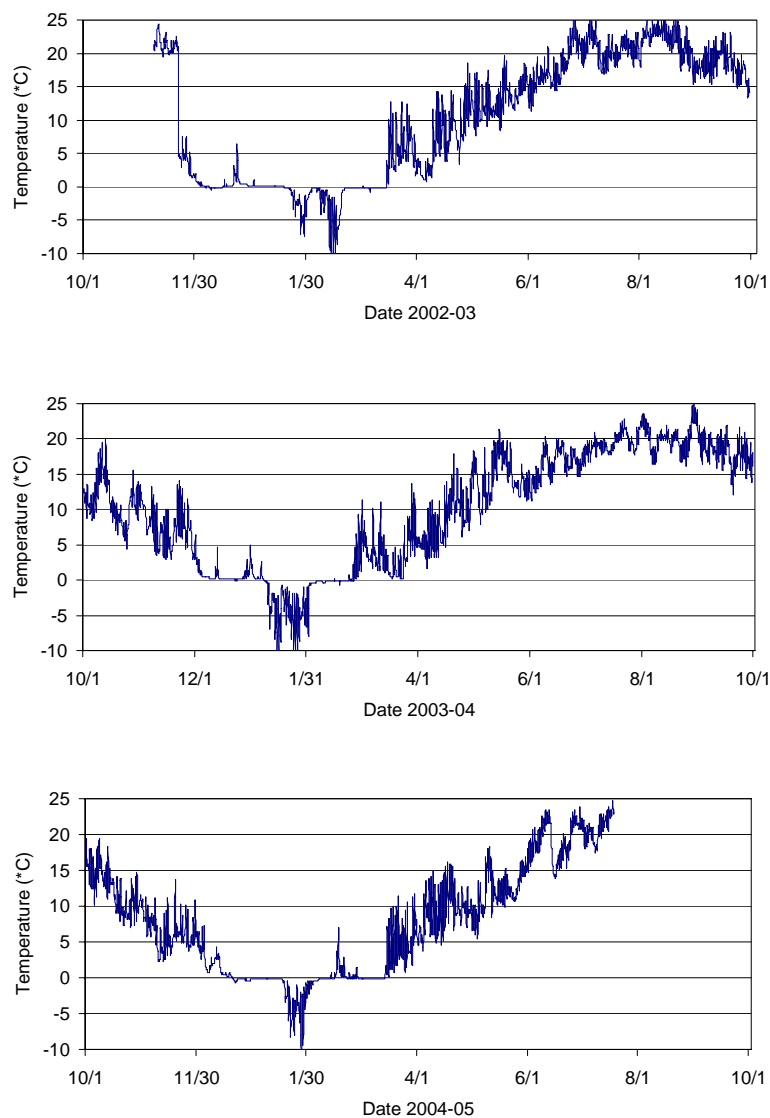
**Figure 24. Soil temperature (°C) at 50-cm depth in the north-facing bank.**



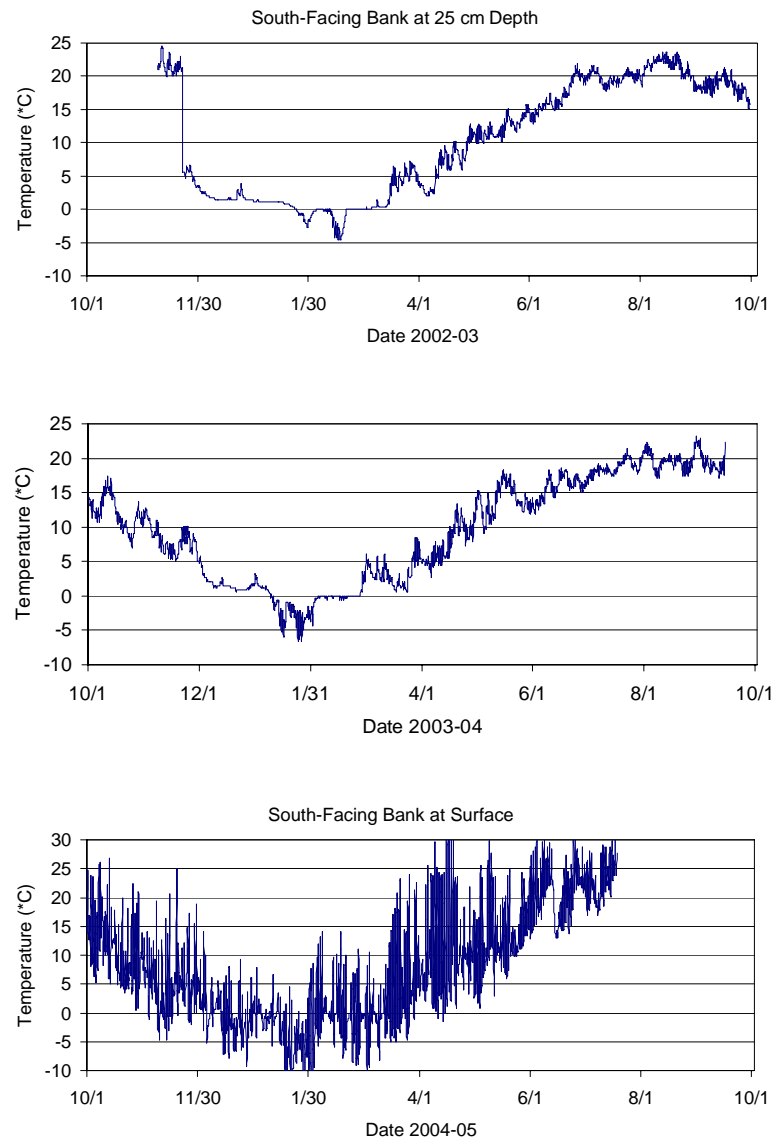
**Figure 25. Soil temperature (°C) at 75-cm depth in the north-facing bank.**

Corresponding soil temperatures of the south-facing bank are given in Figures 26, 27, and 28 for the 10-, 25-, and 50-cm depths. As might be expected, the north-facing bank recorded the lowest soil temperatures and the longest FT durations, exceeding 4 months at shallow depths. In contrast, the south-facing bank site had freezing durations always less than 2 months. The north-facing bank had almost no diurnal soil temperature variations, while the south-facing bank site had by far the most pronounced diurnal temperature fluctuations of any monitored bank. These fluctuations were large at 10 cm (Fig. 26) and still visible at 25

cm (Fig. 27). The 25-cm sensor at the south bank site was pulled by a curious member of the public in 2004–05 and placed on the surface. The result was extremely large temperature fluctuations that approach those of the air temperature.

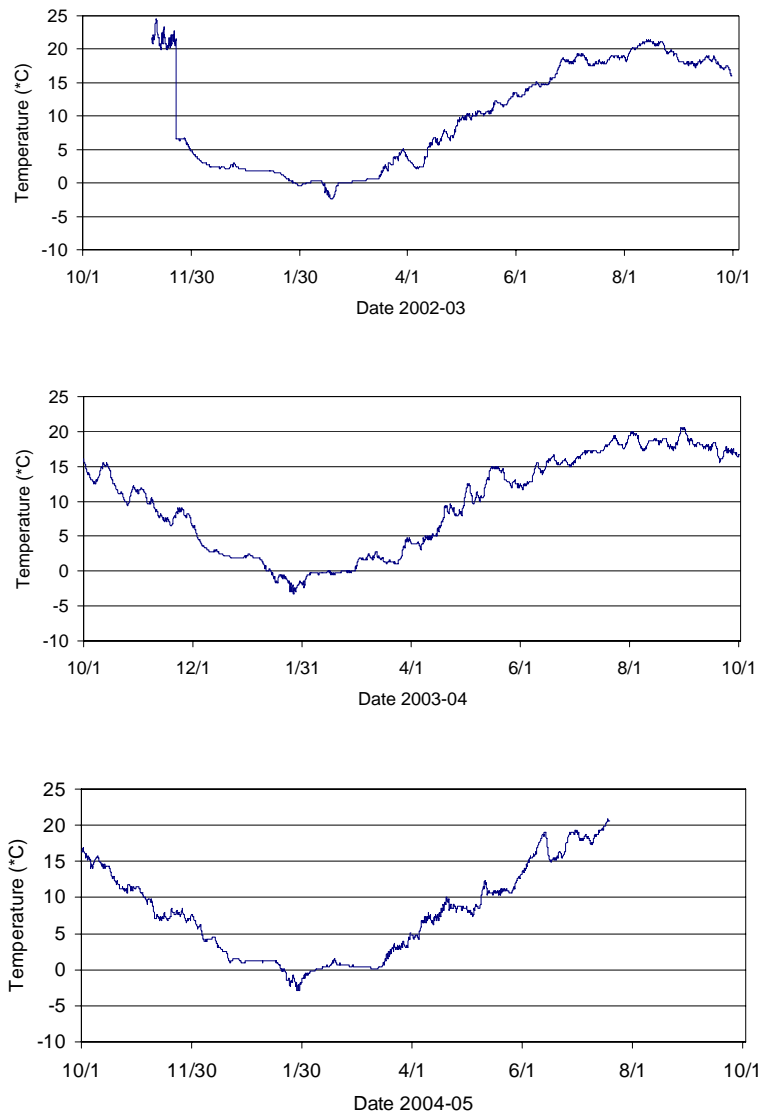


**Figure 26. Soil temperature (°C) at 10-cm depth in the south-facing bank.**



**Figure 27. Soil temperature (°C) at 25-cm depth and at the surface of the south-facing bank.**





**Figure 28. Soil temperature (°C) at 50-cm depth in the south-facing bank.**

We calculated the first derivative of soil temperature with depth,  $\partial T/\partial z$ , for each of the monitored sites. This gradient was largest near the surface at each site, consistent with the location of soil temperature forcing. Gradients at the upper east-facing site were generally larger than those of the lower east-facing site. Gradients at the north-facing bank were generally smallest, while gradients at the south-facing bank were largest and most variable of all. Large soil temperature change with depth at the south-facing bank was probably a result of greater expo-

sure to sunlight, which readily melted snow and augmented the effects of air temperature variations.

Soil and river temperature data are summarized in Table 3 for the frozen and thawing periods. Starting date, minimum and average temperatures, and duration for each year, depth, and site characterize the period of soil freezing. Durations shown in bold type indicate that one or more thaw periods, with soil temperatures of 0°C, are included in the number given. Though complete thaw, indicated by temperature rising above 0°C, did not occur, some amount of FT cycling is the norm at these sites for almost all of the longest subfreezing data records.

**Table 3. Soil and river freeze–thaw data summary.**

| Location          | Depth (cm) | Year    | Freeze     |                 |                       |                 | Thaw       |                 |
|-------------------|------------|---------|------------|-----------------|-----------------------|-----------------|------------|-----------------|
|                   |            |         | Start date | $T_{\min}$ (°C) | $T_{\text{ave}}$ (°C) | Duration (days) | Start date | Duration (days) |
| <b>River</b>      | Variable   | 2002–03 | 12/26      | 0.0             | 0.0                   | <b>88</b>       | 3/24       | 1               |
| <b>Upland</b>     | 10         | 2002–03 | 1/8        | –5.2            | –2.1                  | 77              | 3/26       | 20              |
|                   |            | 2003–04 | 1/8        | –6.8            | –2.5                  | <b>80</b>       | 3/28       | 11              |
|                   |            | 2004–05 | 1/7        | –9.9            | –2.9                  | 82              | 3/30       | 8               |
|                   | 25         | 2002–03 | 1/20       | –3.3            | –1.5                  | 64              | 3/25       | 26              |
|                   |            | 2003–04 | 1/14       | –4.2            | –1.8                  | 76              | 3/30       | 19              |
|                   |            | 2004–05 | 1/17       | –5.5            | –2.5                  | 73              | 3/31       | 14              |
|                   | 50         | 2002–03 | 1/29       | –1.1            | –0.5                  | 49              | 3/29       | 25              |
|                   |            | 2003–04 | 1/23       | –2.0            | –0.9                  | <b>70</b>       | 4/2        | 18              |
|                   |            | 2004–05 | 1/21       | –2.6            | –1.3                  | 67              | 3/29       | 21              |
|                   | 75         | 2002–03 | 3/26       | –0.3            | –0.3                  | 10              | 4/5        | 16              |
|                   |            | 2003–04 | 2/21       | –0.6            | –0.6                  | 17              | 3/8        | 42              |
|                   |            | 2004–05 | 2/22       | –0.9            | –0.7                  | 53              | 4/16       | 9               |
| <b>Upper East</b> | 10         | 2002–03 | 12/2       | –7.1            | –1.9                  | <b>105</b>      | 3/17       | 8               |
|                   |            | 2003–04 | 12/3       | –11.1           | –2.7                  | <b>89</b>       | 3/1        | 26              |
|                   |            | 2004–05 | 12/15      | –11.2           | –2.6                  | <b>90</b>       | 3/15       | 15              |
|                   | 25         | 2002–03 | 12/8       | –5.1            | –1.2                  | <b>106</b>      | 3/24       | 19              |
|                   |            | 2003–04 | 1/8        | –6.7            | –2.0                  | 66              | 3/14       | 30              |
|                   |            | 2004–05 | 1/17       | –6.0            | –1.9                  | <b>72</b>       | 3/30       | 9               |
|                   | 50         | 2002–03 | 1/25       | –2.1            | –0.7                  | <b>55</b>       | 3/21       | 23              |
|                   |            | 2003–04 | 1/22       | –1.5            | –0.9                  | 44              | 3/6        | 47              |
|                   |            | 2004–05 | 1/22       | –1.5            | –0.6                  | <b>58</b>       | 3/22       | 23              |

| Location   | Depth (cm) | Year    | Freeze     |                 |                       |                 | Thaw       |                 |
|------------|------------|---------|------------|-----------------|-----------------------|-----------------|------------|-----------------|
|            |            |         | Start date | $T_{\min}$ (°C) | $T_{\text{ave}}$ (°C) | Duration (days) | Start date | Duration (days) |
| Lower East | 10         | 2002–03 | 12/10      | −0.4            | −0.2                  | 2               | 12/12      | 2               |
|            |            | 2003–04 | 1/8        | −5.7            | −2.1                  | 81              | 2/29       | 31              |
|            |            | 2004–05 | 1/15       | −6.0            | −1.6                  | 59              | 3/15       | 17              |
|            | 25         | 2002–03 | 3/15       | 0.1             | —                     | 0               | —          | —               |
|            |            | 2003–04 | 1/9        | −4.1            | −1.3                  | 52              | 3/1        | 31              |
|            |            | 2004–05 | 1/18       | −4.8            | −1.2                  | 54              | 3/13       | 25              |
|            | 50         | 2002–03 | 3/15       | 1.3             | —                     | 0               | —          | —               |
|            |            | 2003–04 | 1/24       | −0.8            | −0.3                  | 2               | 1/26       | 2               |
|            |            | 2004–05 | 3/4        | −0.2            | −0.1                  | 0               | —          | —               |
| North      | 10         | 2002–03 | 12/5       | −4.4            | −1.2                  | 104             | 3/19       | 31              |
|            |            | 2003–04 | 12/14      | −12.5           | −3.1                  | 103             | 3/26       | 23              |
|            |            | 2004–05 | 12/20      | −12.5           | −3.6                  | 99              | 3/29       | 21              |
|            | 25         | 2002–03 | 1/19       | −3.3            | −1.2                  | 58              | 3/18       | 41              |
|            |            | 2003–04 | 1/8        | −10.1           | −3.1                  | 79              | 3/27       | 28              |
|            |            | 2004–05 | 12/27      | −8.8            | −2.9                  | 92              | 3/29       | 25              |
|            | 50         | 2002–03 | 2/12       | −1.8            | −1.0                  | 39              | 3/23       | 39              |
|            |            | 2003–04 | 1/9        | −8.2            | −2.5                  | 81              | 3/30       | 30              |
|            |            | 2004–05 | 1/16       | −7.6            | −3.0                  | 76              | 4/2        | 25              |
|            | 75         | 2002–03 | 3/12       | −0.3            | −0.2                  | 7               | 3/19       | 32              |
|            |            | 2003–04 | 1/16       | −3.2            | −1.4                  | 58              | 3/14       | 45              |
|            |            | 2004–05 | 1/22       | −2.9            | −1.5                  | 66              | 3/29       | 30              |
| South      | 10         | 2002–03 | 1/22       | −11.5           | −2.6                  | 30              | 2/21       | 23              |
|            |            | 2003–04 | 1/10       | −11.8           | −3.3                  | 31              | 2/10       | 16              |
|            |            | 2004–05 | 1/18       | −10.4           | −2.7                  | 20              | 2/6        | 10              |
|            | 25         | 2002–03 | 1/25       | −4.7            | −1.3                  | 26              | 2/20       | 15              |
|            |            | 2003–04 | 1/11       | −6.6            | −2.4                  | 26              | 2/6        | 21              |
|            |            | 2004–05 | —          | —               | —                     | —               | —          | —               |
|            | 50         | 2002–03 | 2/14       | −2.3            | −1.4                  | 7               | 2/21       | 9               |
|            |            | 2003–04 | 1/15       | −3.3            | −1.5                  | 21              | 2/5        | 24              |
|            |            | 2004–05 | 1/22       | −2.9            | −1.3                  | 14              | 2/5        | 9               |

The ice cover duration on the river during 2002–03 was greater than the period of soil freezing of all depths at the upland site, and lower east-facing and south-facing bank sites. It is also greater than the duration of freezing at the north-facing bank below 10 cm and the upper east-facing bank below 25 cm. With these few exceptions, the river froze earlier in the season than did the bank

soils. Also with few exceptions, the bank soils began to thaw before river breakup, but soil thaw required a much longer time, persisting later in the season than the river ice. Still, the duration of the river ice cover provides a readily observable indicator of the period of seasonally frozen soil.

Comparing upland and upper east sites indicates that the upper east minimum soil temperatures are more extreme, while average temperatures and freezing durations are comparable between the sites. Greater differences can be noted between the upper east and lower east sites. Here, the lower site has higher minimum and average soil temperatures and much shorter freezing durations. While minimum and average temperatures are only slightly lower at the north-facing site relative to the south-facing site, the average duration of freezing is 3–5 times longer at the north-facing site. The north-facing site also has generally lower minimum and average soil temperatures and longer freezing durations than the upper east-facing site. Soils thaw at these sites from both the upper and lower boundaries. Warming air at the surface, and residual heat below the frozen layer, contribute to the thaw. However, thaw induced by ground heat is a very slow process. In years when there is significant freezing at depth, the thaw of these deep soils can be extended. For example, in 2003–04 temperatures reported by the deepest thermistor at the coldest sites, upland, upper east, and north, each indicated that more than 40 days were required for thaw.

### Manual Measurements

Table 4 provides the dates of the manual measurements obtained during site visits. Included is a suite of surface soil measurements; including vane shear strength, penetration resistance, and soil moisture. In addition, soil moisture profiles were obtained near the thermistor locations, and bank surveys were repeated on the instrument, upstream, and downstream profile lines.

**Table 4. Manual data obtained at Norwich, Vermont, sites.**

| Date       | Vane shear strength | Penetration resistance | Surface soil moisture | Soil mois. profiles | Bank profile surveys |
|------------|---------------------|------------------------|-----------------------|---------------------|----------------------|
| 27 Nov 02  |                     |                        |                       |                     | X                    |
| 7 Mar 03   |                     |                        |                       | X                   |                      |
| 18 Jun 03  | X                   | X                      | X                     | X                   | X                    |
| 19 Aug 03  | X                   | X                      | X                     | X                   | X                    |
| 20 May 04  |                     |                        |                       | X                   |                      |
| 23 Jun 04  | X                   | X                      | X                     |                     | X                    |
| 19 July 05 | X                   | X                      | X                     | X                   |                      |

**Table 5. Bank surface strength and soil moisture (mean  $\pm$  std dev).**

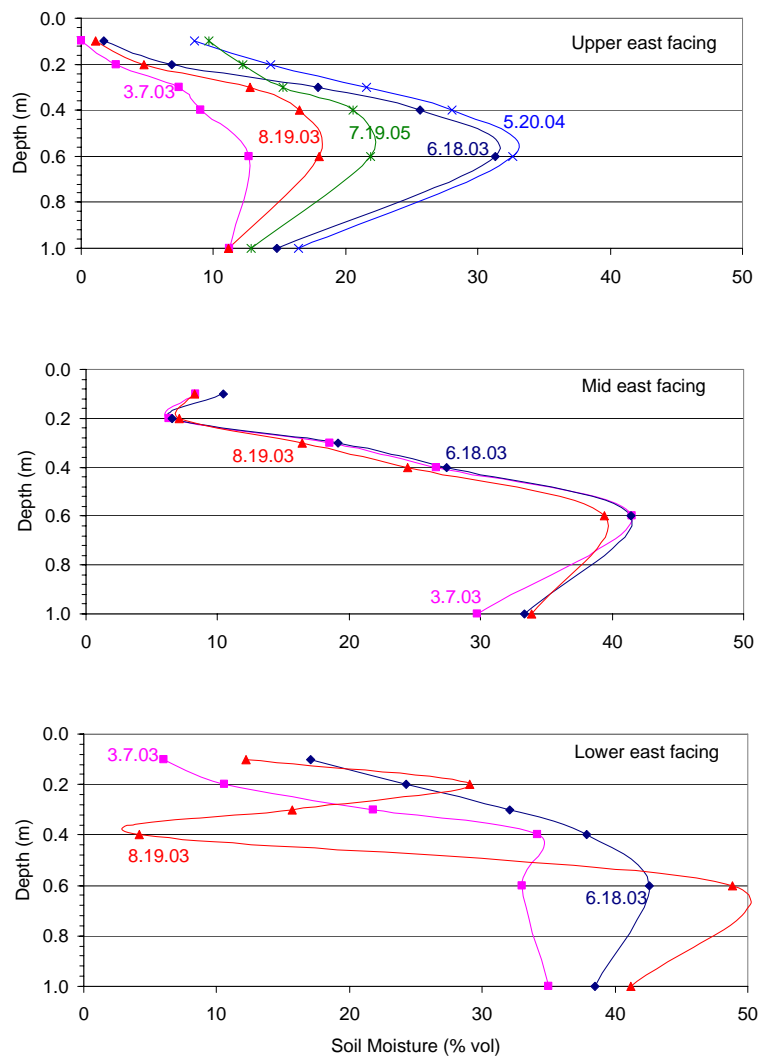
| Location            | Soil Moisture<br>(% by vol) | Vane Shear<br>(kPa)                 | Penetrometer<br>(kPa) |
|---------------------|-----------------------------|-------------------------------------|-----------------------|
| <b>18 June 2003</b> |                             | <b>Near Upstream Profile Line</b>   |                       |
| High Bank           | 13.3 $\pm$ 2.9              | 7.6 $\pm$ 0.7                       | 215 $\pm$ 93          |
| Mid Bank            | 23.2 $\pm$ 1.7              | 8.4 $\pm$ 0.8                       | 487 $\pm$ 70          |
|                     |                             | <b>Near Downstream Profile Line</b> |                       |
| High Bank           | 17.1 $\pm$ 1.3              | 11.2 $\pm$ 1.5                      | 323 $\pm$ 65          |
| Mid Bank            | 12.6 $\pm$ 1.2              | 11.0 $\pm$ 0.8                      | 590 $\pm$ 77          |
| <b>19 Aug 2003</b>  |                             | <b>Near Upstream Profile Line</b>   |                       |
| High Bank           | 15.6 $\pm$ 2.0              | 5.6 $\pm$ 0.9                       | 288 $\pm$ 73          |
| Mid Bank            | 9.7 $\pm$ 1.7               | 8.6 $\pm$ 2.4                       | 408 $\pm$ 52          |
|                     |                             | <b>Near Downstream Profile Line</b> |                       |
| High Bank           | 0.6 $\pm$ 0.3               | 4.9 $\pm$ 1.4                       | 403 $\pm$ 99          |
| Mid Bank            | 7.5 $\pm$ 0.4               | 9.9 $\pm$ 1.8                       | 527 $\pm$ 64          |
| Low Bank            | 18.5 $\pm$ 2.5              | 4.6 $\pm$ 0.6                       | 237 $\pm$ 62          |
| <b>23 June 2004</b> |                             | <b>Near Upstream Profile Line</b>   |                       |
| High Bank           | 9.2 $\pm$ 1.5               | 6.3 $\pm$ 1.2                       | 337 $\pm$ 58          |
| Mid Bank            | 18.6 $\pm$ 3.2              | 12.6 $\pm$ 1.6                      | 321 $\pm$ 14          |
|                     |                             | <b>Near Downstream Profile Line</b> |                       |
| High Bank           | 15.8 $\pm$ 1.2              | 7.2 $\pm$ 3.5                       | 398 $\pm$ 55          |
| Mid Bank            | 10.6 $\pm$ 2.2              | 11.0 $\pm$ 0.8                      | 560 $\pm$ 20          |
| Low Bank            | 12.0 $\pm$ 1.0              | 5.8 $\pm$ 0.8                       | 340 $\pm$ 41          |
| <b>19 July 2005</b> |                             | <b>Near Upstream Profile Line</b>   |                       |
| High Bank           | 8.8 $\pm$ 1.0               | 6.4 $\pm$ 1.6                       | 320 $\pm$ 57          |
| Mid Bank            | 14.8 $\pm$ 1.3              | 10.0 $\pm$ 3.2                      | 322 $\pm$ 51          |
|                     |                             | <b>Near Downstream Profile Line</b> |                       |
| High Bank           | 10.2 $\pm$ 1.6              | 8.8 $\pm$ 3.6                       | 415 $\pm$ 49          |
| Mid Bank            | 9.4 $\pm$ 1.9               | 9.0 $\pm$ 1.1                       | 507 $\pm$ 51          |
| Low Bank            | 9.6 $\pm$ 2.3               | 5.7 $\pm$ 0.9                       | 282 $\pm$ 65          |

Bank surface strength and soil moisture data are summarized in Table 5. Surface soil moistures collected at all of the strength measurement locations tend to decrease through the summer. There is no clear correlation between the strength and soil moisture measurements. Mean penetrometer resistance varied between 215 and 590 kPa on 18 June 2003, providing the range for the complete measurement set. The high bank location upstream (290 kPa) and the low bank location downstream (286 kPa) had the lowest overall mean penetration resistance, while the mid-bank downstream mean was highest (546 kPa) with consistent

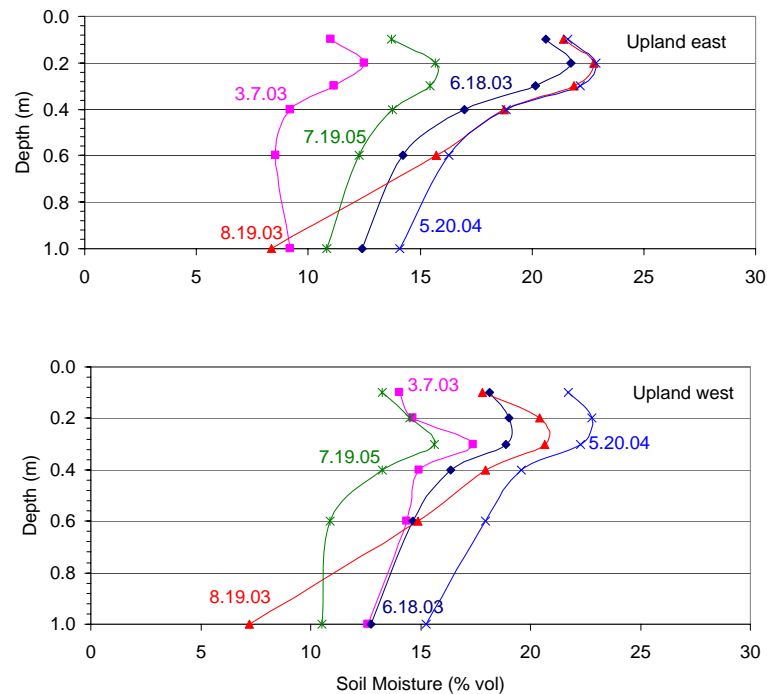
readings all over 500 kPa. Mean vane shear measurements also varied widely, from 4.6 to 12.6 kPa. Mid-bank locations both upstream and downstream had the highest vane shear strengths with overall means of 9.9 and 10.2 kPa, respectively. The downstream low bank location had the lowest overall mean vane shear of 5.4 kPa. The soils at the low bank location downstream were relatively weak compared with much stronger soils at the mid-bank upstream and downstream locations. Both of these strength measures indicate significant variability in the surface soils, probably related to variable soil characteristics and grain size composition at locations along the east-facing bank.

Soil moisture profile data were obtained at all available access tubes on the dates indicated in Table 4. However, even minor movement in the upper meter of soil can deform the access tubes, preventing the measurement. The shapes of the soil moisture profiles along the east-facing bank instrument line are consistent through time (Fig. 29). All of the upper slope profiles indicate maximum soil moisture near 0.5 m with lower values shallower and deeper. The mid-slope profiles are similar, with the maximum point shifted down to 0.6 m and with generally greater deep soil moisture. This same trend continues at the lower slope, where soil moisture below 0.5 m is consistently high, likely caused by high water levels in the reservoir. The upslope soil is generally dryer and variable, the mid-bank is wetter with little variation, and the lower bank is wettest and also variable. The mid- and lower east-facing access tubes were deformed and not usable after 2003, while all other access tubes remained in service through 2005.

Upland soil moisture profiles on the instrument line, given in Figure 30, are consistent with each other and through time. These profiles show lower soil moistures than on the slope, peak moisture consistently between 0.2 and 0.3 m, and minimum soil moisture at 1 m depth. Upland soil near the bank crest is generally drier with less seasonal variation than soil below the crest. Figure 31 presents soil moisture profiles through time for the upper and mid-north-facing bank. Soil moisture of the upper slope is uniform and relatively low through the 1-m depth. A seasonal trend can be discerned, with wetter soil in the spring, drying into the summer. Soil of the mid-north-facing bank is relatively dry in the upper 0.2 m, becoming wetter and more uniform below the 0.3-m depth. This profile also shows seasonal trends, dryer in late winter and summer and wetter in spring. Similar to the instrument profile line of the east-facing bank, the soil of the upper north-facing bank is drier than that of the mid-bank. Overall, the north-facing bank is drier than the instrument line of the east-facing bank, possibly a result of more dense vegetation or local differences in soil composition.



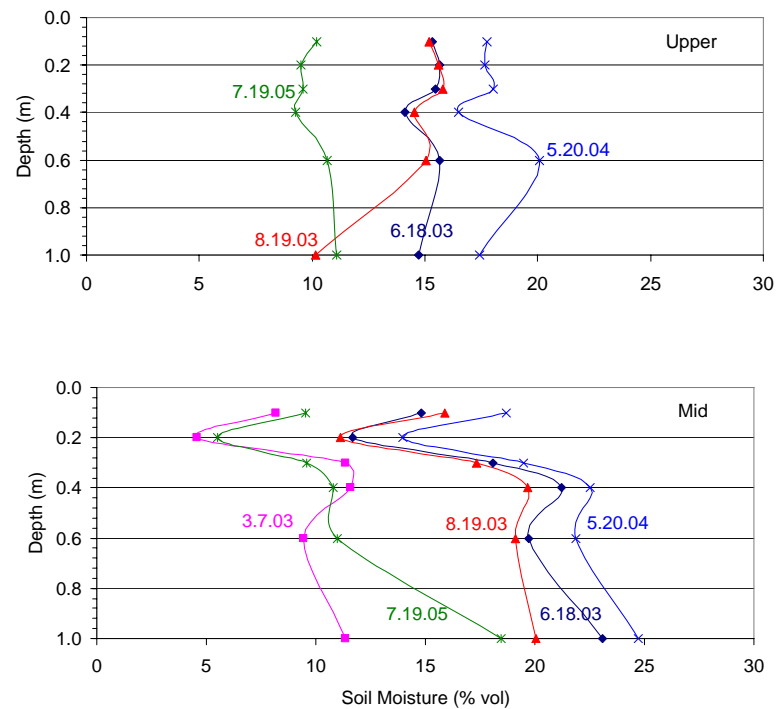
**Figure 29. Soil moisture profiles through time on the east-facing bank at the “instrument” profile line near top, mid-, and bottom.**



**Figure 30. Soil moisture profiles through time of the upland surface on the “instrument” profile line, east and west.**

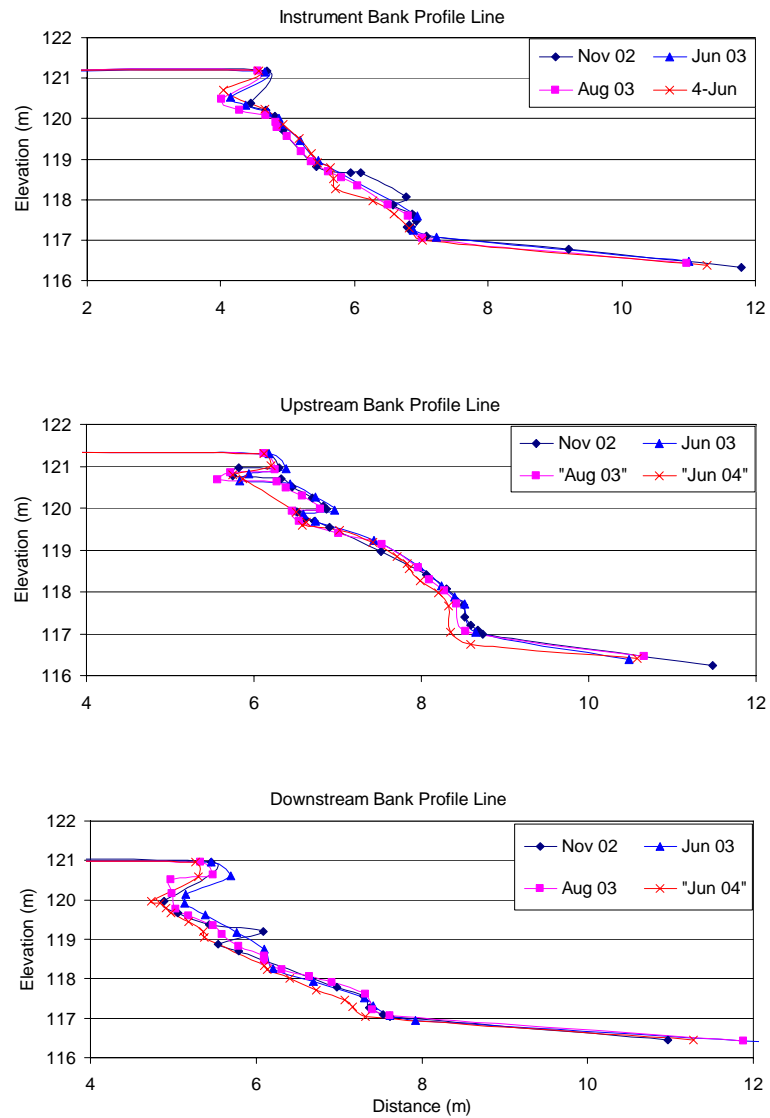
Four surveys of the profile lines on the east-facing bank were conducted between November 2002 and June 2004, with results presented in Figures 32 and 33. The profile changes through time shown in Figure 32 indicate banks that are undergoing surface erosion, not failure along deeper planes of weakness, and give a sense for the times when these changes occurred. However, loss of access to mid- and lower east-facing slope soil moisture tubes at the instrument line indicates some deeper soil movement. Cavity development near the top of the bank on this same line can be noted in these survey results and has continued in 2005. These surficial bank changes validate the importance of the surface property measurements obtained. Banks that are frozen in winter and subject to minimal precipitation in summer should not erode during those periods. The most probable periods for bank erosion are during fall prior to the freeze, and during the spring following thaw. Small bulges in each profile line that disappeared over the FT season indicate a likely role of FT in the surficial upland erosion of the bank.



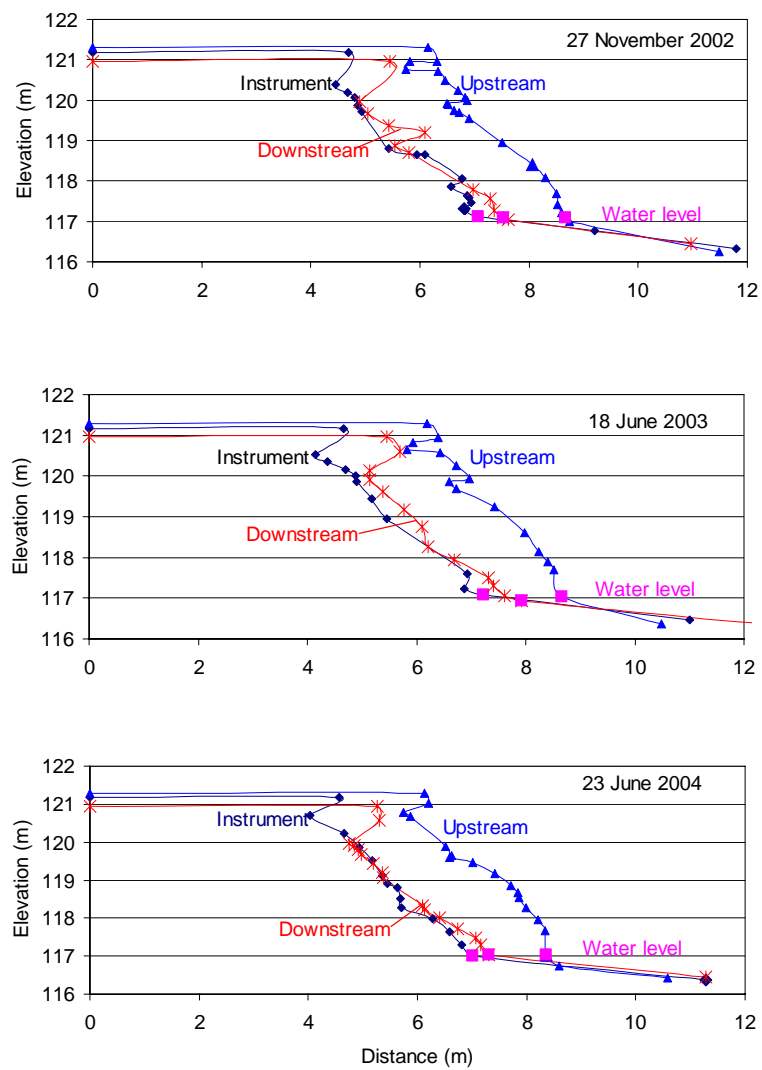


**Figure 31. Soil moisture profiles through time of the north-facing bank, upper and mid-.**

The profile lines are compared with each other for each of the years of the study in Figure 33. In this form the changes along each profile can be more readily discerned, and similar average slopes are evident. Bank recession has proceeded steadily along all three profiles, and slope similarities are maintained through time despite variable soil characteristics and large differences in density of the vegetative cover. These similarities together with significant erosion at the base of the bank (Fig. 4) indicate that a primary forcing is by hydraulic processes of the river. Waves and fluctuating water levels of Wilder Reservoir were active in removing both fine sediments and native materials from the base of the bank (Fig. 4 and 6) over the full monitored length.



**Figure 32. Repeat surveys through time of instrument, up-stream, and downstream bank profile lines.**



**Figure 33. Instrument, upstream, and downstream bank profile lines compared through time.**

## 6 DISCUSSION AND CONCLUSIONS

The primary purposes of the field program were to evaluate: 1) the depth and duration of soil FT, and the effect of orientation and soil moisture on these parameters, 2) the effects of soil FT on erosional processes, 3) the timing, effects, and depth of any slope failures of the east-facing bank, and 4) the hypothesis of soil FT as a primary cause of slope instability.

The extent of freezing was very different at the east-facing upper and lower bluff face sites on the instrument bank profile line, separated by only 3 m. The lower site has higher minimum and average soil temperatures and much shorter freezing durations. The upper bank face site had freezing temperatures below 50 cm in each of the three winters. In 2002–03, the lower bank face site had minimal freezing at the 10 cm depth and no freezing with temperatures above 1.3°C throughout the winter at 50 cm. High reservoir water levels occur regularly, increase the lower slope soil moisture, and supply a reservoir of latent heat that limits soil freezing. This interpretation is consistent with the results of Ferrick et al. (2005) that the saturated soils of the bluff at Allegan, Michigan, lead to relatively high soil temperatures in winter and minimum depths of frost penetration.

The orientation of the monitored bank is also very important to the soil temperature regime. While minimum and average temperatures are only slightly lower at the north-facing site relative to the south-facing site, the average duration of freezing is 3–5 times longer at the north-facing site. The north-facing bank recorded the lowest minimum and average temperatures and the longest frozen soil durations of any site, exceeding 4 months at shallow depths. In contrast, the south-facing bank always had freezing durations less than 2 months. The north-facing bank had almost no diurnal soil temperature variations while the south-facing bank site had by far the most pronounced diurnal temperature fluctuations of any monitored bank. Mild south-facing bank soil temperatures and large temperature change with depth probably result from increased exposure to sunlight, which readily melts snow cover and augments the heat flow resulting from air temperature variations.

The river generally froze earlier in the season than the bank soils. The thawing of bank soils began before river breakup, but soil thaw required a much longer time and extended later in the season than the river ice. Still, the period of river ice cover provides a valuable and readily obtained estimate of that of the seasonally frozen soil. Though complete soil thaw during the frozen period, with temperature rising above 0°C, did not occur at any site, some amount of FT cycling is the norm for almost all of the longer subfreezing data records. Final soil

thaw at these sites in the spring occurs from both the upper and lower boundaries. Warming air at the surface, and residual heat below the frozen layer contribute, but thaw induced by ground heat is very slow. In years where significant freezing occurs at depth, the thaw of the deeper (0.5–0.75 m) soils can extend over more than 40 days at the colder sites.

The changes to the east-facing bank that occurred during this study were surficial and erosional, and not caused by failure along deeper planes of weakness. However, loss of access to mid- and lower east-facing slope soil moisture tubes indicates that some deeper soil movement also occurred. Bank retreat was slow but persistent at all profile lines. Unlike Allegan, where saturated soils are common and remediation of instability by pumping shows promise (Ferrick et al. 2005), saturated soils here are limited to the high water level of the reservoir and below. As a result, groundwater is not a large factor in bank recession at the Connecticut River site. However, significant FT cycling does affect bank soils. Banks that are frozen in winter and subject to minimal precipitation in summer should not erode during those periods. Therefore, the most probable periods for bank erosion are during fall prior to the freeze, and during spring following thaw. Rain and snowmelt runoff are then able to readily move weakened sediments down slope (Ferrick and Gatto 2005). A probable role of FT to minimize the resistance of surface soils to erosion is indicated by this study, but a more complete and quantitative understanding of bank processes affected by FT will require carefully designed and controlled laboratory experiments.

Hydraulic forcing by waves and fluctuating water levels of the Wilder Reservoir is active at the base of the monitored bank, moving both fine sediments and native bank materials offshore. Soil losses from the base of the bank and bank retreat, indicated by the measured profiles, observations of undercutting, and the development of native cobble bed armoring, maintain unstable slope steepness and support continuation of upslope erosional processes. Any engineered solution of this bank recession problem must restrain further landward movement at the base of the bank, allowing a stable upper slope to become established over time.

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